CR 86218

[redacted]

POLHEMUS NAVIGATION SCIENCES, INC.

P.O. BOX 1011; BURLINGTON, VERMONT; 05401; PHONE 802/658-1450

PNSI-TR-69-0301-

NAVIGATION/TRAFFIC CONTROL STUDY FOR V/STOL AIRCRAFT

(Final Report)

VOLUME I - SUMMARY

March 1969

Prepared under Contract No: NAS-12-2024
by
POLHEMUS NAVIGATION SCIENCES, INC.
Burlington, Vermont
(formerly: Ann Arbor, Michigan)

for: Electronics Research Center
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

Polhemus Navigation Sciences, Inc. was awarded a contract by the National Aeronautics and Space Administration to conduct a study entitled "Navigation/Traffic Control Study for V/STOL Aircraft" (NAS-12-2024). The goal of the study was to provide recommendations to NASA regarding the solution of domestic air traffic control/airborne navigation problems envisioned for 1975-1985. The program was sponsored by the Navigation and Guidance Branch, Electronics Research Center, Cambridge, Massachusetts. Mr. J. R. Coonan served as Technical Monitor for NASA/ERC. Principal investigator for PNSI was Mr. Thomas T. Trexler.

This three-volume final report presents summary results of the NAVTRAC study covering project activity from August 1969 through March 1969. It describes a broad-scope analysis which identifies, from the pilot's viewpoint, the desirable performance characteristics of an advanced navigation/traffic control system for aircraft operating in an environment consisting of V/STOL, CTOL-jet, SST, and general aviation aircraft. A number of recommendations are made for the immediate further research and development of technology related to future airborne avionics systems and air traffic control. The recommended development program has a two-fold design objective: validation of the "Flight Plan Reference/ATC" concept and verification of the effects of automation on pilot workload. Recommendations are made for development of technology associated with NAV SAT and ground-based hyperbolic systems. They include: development of a digital software computer program; man-machine simulation(s) for VTOL and general aviation aircraft; hardware bench and field tests; and qualification flight tests.

The assistance of the following individuals who contributed substantially to the preparation of this document is acknowledged:

Mr. William L. Polhemus	Operations Consultation
Mr. Donald W. Richardson	Engineering Direction
Mr. Linus E. Lensing	Technical Editing and Publication
Mr. Edwin McConkey	Radio Systems Engineering
Mr. Eric H. Bolz	Radio Systems Error Analysis
Mr. Steven C. Lesak	Pilot Workload Studies

PRECEDING PAGE BLANK NOT FILMED.

ABSTRACT

The Navigation Traffic Control Study for V/STOL Aircraft (NAVTRACS) develops recommendations for the further research and development of air traffic control/navigation related technology. The desired performance characteristics of an advanced navigation/air traffic control system for the 1975-1985 domestic air transportation environment are developed from the cockpit viewpoint. V/STOL, CTOL-jet, SST, and general aviation aircraft are considered. The advanced system embodies two new concepts: a Flight Plan Reference System and Limit Logic. The concepts assume the availability of area navigation aids. Five candidate systems are evaluated: NAVSAT, ground based hyperbolic (Decca, Loran C and Omega) and rho theta integrated with course line computer.

Enroute, terminal area and approach and landing requirements are considered. Area navigation, in this context, provides two capabilities: required horizontal position information for the pilot, and ATC system-required surveillance information. To generate the precision required for approach and landing of carrier aircraft, a differential NAVSAT and/or ground based hyperbolic capability must be incorporated into the system if individual runway instrumentation is not to be used.

Acceptability of each area navaid is evaluated through use of comparative pilot workload analysis. For purpose of this study, the pilot workload approach is used to determine desired system level(s) of automation. Detailed Event Sequence Diagrams which cover both VFR and IFR operations define the pilot's tasks of navigation, communication, aircraft control, and system monitoring. . . . . and show the interface between airborne system and ATC. To insure a broadly based workload assessment, several configurations of general aviation and air carrier-type avionics systems are included in the tradeoff analyses.

Volume I of the report contains an overall summary of the results of the study. Volume II (Technical) discusses the technical approach used in the study and describes the results of various tradeoff analyses which lead to the reported conclusions and recommendations. Volume III (Appendices) documents the background technical data generated to support the analyses and system definition.

PRECEDING PAGE BLANK NOT FILMED.

TABLE OF CONTENTS

TABLE OF CONTENTS (contd.)

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF SYMBOLS AND NOMENCLATURE

o Arabic Letter Listing (lower case)

a	aircraft acceleration
a	radius of the earth
a/c	aircraft
ackn	message acknowledgement
c	speed of light
d	distance from calibration point to user
d	distance from transmitter to user
dm	distance between point of closest approach and transmitter
do	distance between aircraft and point of closest approach
do	calibration point
dP	position error vector
d rms	rms statistic of radial repeatability error
dT	TD error
f	carrier frequency (mHz)
f k Hz	carrier frequency (kHz)
f	frequency
f30, f31	frequency code of third (3) approach path (outer and inner marker beacon)
g	earth gravitational acceleration
g	general aviation aircraft density
g1, g14	general aviation candidate navigation systems
h	altitude
hn1, hn2.. hn3	altitude of the final approach waypoints
ho3, hi3, ho3	command altitude at outer, inner marker beacon and pad, respectively; for the third (3) approach path
$\underline{n}$	rms noise field strength
s	horizontal distance in VOR cone of silence
s_h	an altitude
s_{at}	an along track distance
s_{ct}	a cross track distance
s	LaPlace operator
t_a	along track separation
t_c	time delay due to propagation over the earth
v1 v10	aircarrier candidate navigation systems

o Arabic Letter Listing (caps)

A	heading
ABBR	abbreviated report
AC	aircarrier
Ackn	message acknowledgement
ADF	automatic direction finder
AFCS	automatic flight control system
A-G	air-to-ground
AIREP	air report
AILS	advanced instrument landing system
AP	autopilot
ARINC	Aeronautical Radio, Inc.
ARSR	air route surveillance radar
ARU	attitude reference unit
AS	airspeed
ASDE	airfield surveillance detection equipment
ASR	airport surveillance radar
ATA	Air Transport Association
ATC	air traffic control
AT	along track
ATIS	automatic terminal information service
ATT	attitude
ALT	altitude
B	TD receiver constant (rad/sec)
Bw	bandwidth of receiver r.f. section (Hz)
CAS	collision avoidance system
CAS	calibrated airspeed
CAT I, CAT II, CAT III	category or landing conditions
CCC	communication, command and control
C/D	control/display
Comm	communication
CPU	central processing unit
CRT	cathode ray tube
CT	cross track
CTD	cross track distance
CTOL	conventional takeoff and landing
CLC	course line computer
CLR	clearance
CW	continuous wave

o Arabic Letter Listing (caps) - (cont'd)

C	operator transportation log
D	distance
DA	drift angle
DG	directional gyro
DI	deviation indicator
DIST	distance to go
DOC	direct operating cost
DR	dead reckoning
D rms	rms statistic of radial predictability error
DD rms	rms statistic of radial TD system error
DTD	differential time difference
DTD (GB)	differential time difference - ground based
DTD (NS)	differential time difference - navigation satellite
DTG	distance to go
DME	UHF distance measuring equipment
E	east
E	rms field strength
Eg	rms ground wave field strength
Es	rms sky wave field strength
EET	estimated enroute time
ESD	event sequence diagram
ETA	estimated time of arrival
FAA	Federal Aviation Administration
FL	flight level
FPA	flight path angle
FSS	flight service station
FSK	frequency shift keying
G	transformation matrix
GA	general aviation
G-A	ground-to-air
GA1, GA2, GA3	classes of general aviation aircraft (p 2-11)
GDOP	geometric dilution of precision
GBTD	ground based time difference
GMT	Greenwich Mean Time
GS	landing system glideslope
GS	ground speed
HDG	heading
HF	high frequency
H1, H2, H3	hold waypoints
H(s)	transfer function of receiver tracking loop
HSD	horizontal situation display
HSI	horizontal situation indicator
IAS	indicated airspeed
ID	identification
IFR	instrument
ILS	instrument landing system
IMB	inner marker beacon
IMC	instrument meteorological conditions
IMU	inertial measurement unit
INS	inertial navigation system
IP	intercept point
IRU	inertial reference unit
JFK	John F Kennedy International Airport
K	operator gain
K	propagation constant
KCAS	knots, calibrated airspeed
KTAS	knots, true airspeed
Lg, Long	aircraft longitude
LgD	waypoint or destination longitude
Lg_o	estimate of aircraft longitude
Lt, Lat	aircraft latitude
LtD	waypoint or destination latitude
Lto	estimate of aircraft latitude
LGA	La Guardia Airport
LF	low frequency
LN1, LN2, LN3. LWP1. .	groundpoints or waypoints which define a final approach path
LOC	landing system localizer
LOP	line of position
LOS	line of sight
LWP1, LWP2, LWP3 .	waypoints which define a final approach path (used with LN1, LN2)

LIST OF SYMBOLS AND NOMENCLATURE (continued)

o Arabic Letter Listing (caps) - (cont'd)

MAA	maximum acceptable altitude
MBR	marker beacon receiver
MEA	minimum enroute altitude
MMD	moving map display
MOCA	minimum obstruction clearance altitude
MRA	minimum reception altitude
M/S	master/slave combination
N	north
N G	navigation and guidance
Nr	number of VOR radials
NAV SAT	navigational satellite
N^2	noise power spectral density
N_p	peak noise voltage
NAVTRACS	Navigation Traffic Control Study
N_A	number of instantaneous users requiring service
NAV	navigation
NOTAMS	notices to airmen
OMB	outer marker beacon
OP	operate mode
P	potential candidate airport for ATC
Pe (s)	phase of the error signal
Pi (s)	phase of the input signal
Po (s)	phase of the output signal
Pr	radiated power (db above one kW)
Pss	steady state phase error
PAR	precision approach radar
PF	position fix
POS	position; latitude, longitude
PPI	pulse position indicator
PT	procedure turn
PVOR/PDME	precision VOR/precision DME
PWI	position warning indicator
Q (s)	position output of inertial platform
R	horizontal distance to a VOR facility
R	general aviation reliever airport
Ro	initial range to waypoint
Rp (d)	spatial autocorrelation function of predictability error
Rr (d)	spatial autocorrelation function of repeatability error
Ro	earth radius
Rpt	report
R/T	receiver/transmitter
RTE	route
RVR	runway visual range
S	south
S	rms signal field strength
Sp	peak signal voltage
SID	standard instrument departure
SID	sudden ionospheric disturbances
SIGMET	significant meteorological conditions
SOP	surface of position
SSR	secondary surveillance radar
SST	supersonic transport
STD	standard
STOL	short takeoff and landing
(T)	airport with ATC tower
T, t	time
Tk	track
To, to	initial time
TAE	track angle error
TAS	true airspeed
TD (GB)	time difference - ground based hyperbolic
TD (NS)	time difference - navigation satellite
TD1, TD2..	time difference signal output
TKE	track angle error
TMA	terminal area
T/O	takeoff
TTG	time to go

Arabic Letter Listing (caps) - (cont'd)

V, v	velocity output of inertial platform
Vat	along track speed
V_g	ground speed
Vct	cross track speed
VFR	visual flight rules
VLF	very low frequency
VMC	visual meteorological condition
V_{MO}	maximum structurally safe operating speed
VOR	very high frequency omnidirectional radio range
VOR (H)	high altitude (jet route) VOR facility
VOR (L)	low altitude VOR facility
VOR (T)	terminal VOR facility
VREF	speed reference for slant track glideslope
WPT	waypoint
WPT1, WPT2, .	the sequence of waypoints which comprise a flight plan
VWPT	vector waypoint, a waypoint commanded by ATC which differs from the original flight plan waypoint
VWPT1, VWPT2,	the sequence of waypoints which comprise a revised flight plan commanded by ATC
Z_A	altitude
Z_{AC}	command altitude

o Greek Letter Listing (lower case)

α	attenuation constant
α	proportionality constant
βm	magnetic course to waypoint
γ	time between pulses
δ	drift angle
δt	time error
ϵa	accelerometer bias error
ϵg	gyro drift rate
$\epsilon \gamma$	deviation of actual from command glideslope on slant track
θ	bearing to a waypoint, facility, or hazard
θ	phase error
λ	wavelength of signal
ρ	slant range to a waypoint, facility, or hazard
ρ	aircarrier and military aircraft density
σ A	3σ heading error
σ AT	3σ along track error
σ CT	3σ cross track error
σ d	standard deviation of position error
σ GS	1σ glideslope error
σ h	3σ altitude error
σ LOC	1σ localizer error
σ P1, σ P2.	standard deviation of time error on each path
σ t	standard deviation of time error
σ TD1, σ TD2	standard deviation of time difference error
σ v	3σ speed error
σ	standard deviation of phase error
τA	operator anticipation time constant
τL	operator error smoothing lag time constant
τN	operator short neuromuscular delay
τT	position fixing frequency in terms of track error
τu	position fixing frequency in terms of NAVSAT
ϕ	relative phase between signal and error voltage
υ	ionospheric reflection coefficient
ω	radian frequency of carrier signal

o Greek Letter Listing (caps)

Δ	an increment in an associated variable
ΔCT	an increment in crosstrack distance
ΔETA	an increment in ETA
Δf	fractional frequency deviation
Δfuel	an increment in fuel volume
ΔZ, ΔH	an increment in altitude
Δrms	rms statistic of radial DTD system
ΔTD1, TD2.	differential time difference calibration signals
ΔV	an increment in speed

INTRODUCTION

A number of authorities have pointed out that the constant evolution of the U. S. transportation system has been one of the principal motivators to this country's progress. Air transport, a key element in this evolving system, is reaching the point of being able to satisfy almost all of the travel needs of the American public. A major inhibiting factor, however, is the well-advertised problem of limited system capacity . . . . . a limitation brought on by a combination of technical and operational problems.

While there is physically more than adequate airspace to meet the needs of all categories of aviation through the next fifteen years, limitations in existing ground and airborne systems require the reservation to each aircraft of an inordinately large volume of airspace. The use of largely manual surveillance and control procedures also seriously affects the capability of the overall air transportation system. The lack of availability of adequate airport facilities at a number of key airports also contributes significantly to the problem.

At this juncture one can ask the question "What technologies could or should be encouraged through federal support in an effort to remove the major constraints on growth of air transport?"

Among the research efforts supported by NASA-ERC in an effort to answer this and similar questions was the study reported on in this volume . . . . . the identification from point of view of a pilot, of the desirable performance characteristics of an advanced navigation/traffic control system suitable for the 1975-1985 time frame. In this particular study the point of view of the User of the system was to be the principal criterion of acceptability . . . . . a point of view motivated by concern for safety, schedule reliability, minimum expense and minimum workload.

The users of the air transport system were generally defined as general aviation and commercial air carriers. Except for its influence on estimates of future enroute and terminal area traffic, military aviation was not considered in this study. General aviation was subdivided into three categories related to performance and cost of vehicle. Four categories of commercial air carrier were assumed.

The contract required that four navigation system configurations be evaluated: Decca, Loran C, NAV SAT, and radio-inertial. A variant of the time difference systems was postulated, called differential time difference, in an effort to meet required approach and landing minima.

The results of the evaluation and analysis performed in this study indicate that two of the major constraints on continued growth of the air transport system, which could be alleviated either through increased air and ground system automation and/or improved avionics technology, are: (1) lack of the navigation performance requirements, and (2) the intolerably high workload which will be experienced in future cockpits if automation of

certain navigation and communication functions is not achieved. Conversely, major improvements in system capacity and system safety can be realized through use of a surveillance and control concept which embodies: (1) a form of mandatory flight plan reference with retrievable flight plan for all Users, (2) control-by-exception or Limit Logic, (3) automated communications, (4) three-dimensional area navigation, and (5) an Automated Ground System.

The new technologies recommended in this study tor support by NASA could create the necessary airborne capability.

Objectives

The Navigation/Traffic Control Study (NAVTRACS) developed, from the viewpoint of the pilot, an advanced navigation/air traffic control system capable of satisfying the demands for service and safety of all general aviation and air carrier aircraft forecast to be operational in the 1975-85 time period.

The reported conclusions of the study describe requirements for increased levels of automation in both airborne and ground-based systems, for an area navigation capability incorporating methods for airborne generation of surveillance and control information, for improved terminal area navigation capability, and for major reduction in levels of cockpit workload.

Recommendations have been made for new technologies, further studies and field experiments, including both simulation and flight test, which will aid in verifying the conclusions. These results thus permit the NASA to identify a number of exploratory and/or development programs which offer the potential of greatly improving the capacity and efficiency of the total air transportation system (ATS).

Study Approach

The requirements on the advanced navigation/air traffic control system were developed from three principal sources of information.

The first was a data base developed by the study team which included a traffic activity forecast, a survey of pilot information requirements, a review of performance characteristics of selected air carrier and general aviation aircraft, an internally generated description of aircraft missions and profiles, and a cockpit workload model devised by the study team.

The second source of requirements on the advanced system was developed from an evaluation of the required features of an ATC system. Since the ATC system must be provided with the independent and secure surveillance information which positively indicates vehicle position and velocity, the system must possess a closed loop command link and a capability to at least semiautomatically relay and display advisory information.

The third source of requirements on the advanced system comes from the need to provide an area navigation, approach and landing system of sufficient accuracy and precision to permit relatively unrestricted movement of all Users of the air transport system regardless of weather and/or traffic density.

Study Constraints

In the course of developing the advanced system the study team was asked to determine the relative suitability of four candidate navigation configurations (Decca, Loran C, NAV SAT and a hybrid radio-inertial system) to meet the navigation and surveillance performance requirements. Because of the accuracies required in the approach and land phases of flight a modified approach, called differential-time-difference, was postulated and evaluated for its applicability.

An advanced ATC system was postulated and used as a model for evaluation of a number of candidate airborne systems. The cockpit workload model was then exercised in an effort to quantify system performance benefits. A limited assessment was made of the cost of ownership of the candidate navigation aids using the existing VOR/DME system as the datum for judging cost benefit payoff. Finally, a most promising candidate system was nominated.

SUMMARY

A candidate navigation/air traffic control system was developed and evaluated which embodies operational characteristics reflecting the cockpit point of view. Its principal criterion of acceptability was "effect on cockpit workload."

Three categories of general aviation aircraft and four categories of air carrier aircraft expected to be operational during the 1975-1985 time frame were evaluated.

The paragraphs which follow summarize the elements of the study:

(1) Data Base - traffic forecast, categories of users, user missions and profiles, user subsystems, general cockpit information requirements and workload methodology.

(2) Required Features of the ATC System - separation criteria, flight plan control, radar surveillance, communication system requirements.

(3) Required Features of the Area Navigation, Approach and Land Systems - approach and land criteria, area navigation criteria, qualitative summary of area navigation requirements.

(4) Candidate Navigation Aids - Decca, Loran C and NAV SAT; other candidate systems, the operational requirements, accuracy requirements and capabilities.

(5) Configuration of an ATC System - the concept, flight plan reference, retrievable flight plan, limit logic equipment, operational considerations.

(6) Evaluation of Workload and Automation Benefits - workload assessment methodology, airborne systems - GA, air carrier, methods for system use, communication workload tradeoffs, navigation workload tradeoffs.

(7) Selection of Most Promising Candidate - system performance benefits, system cost benefits, system ranking.

(8) Summary and Conclusions

(9) Recommendations

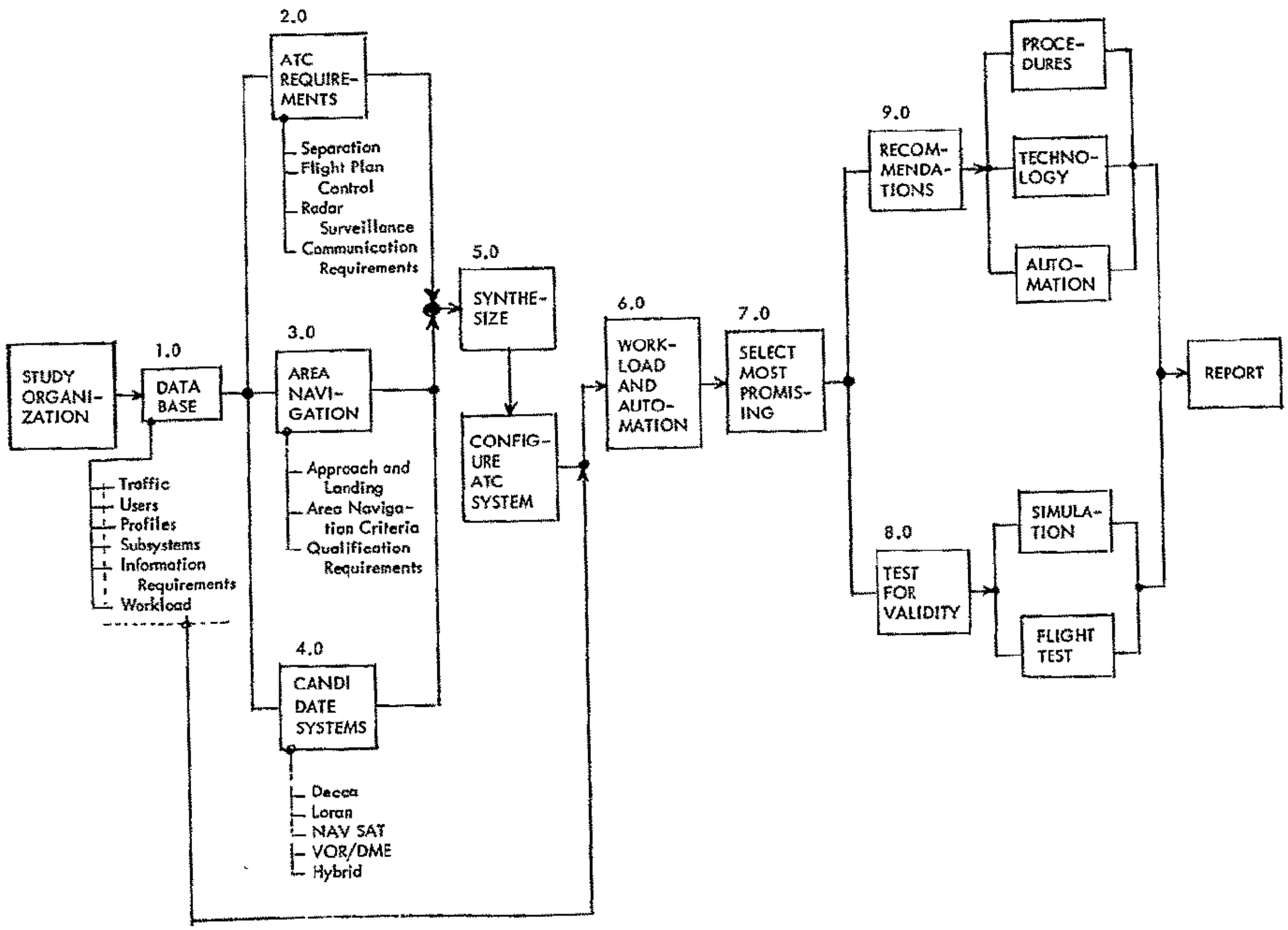


Figure I. Study Methodology

1. THE DATA BASE

1.1 TRAFFIC ACTIVITY FORECASTS

Traffic activity forecasts derived from data supplied by the technical monitor were used to compute navigation and communication requirements. Activity forecasts for six representative Centers are presented in Table I. Two categories of User are identified, general aviation and air carrier (including military aircraft movements). The min/max range of peak-minute traffic is summarized in Table II.

The peak-minute densities were tabulated for each 100 square miles of a typical sector within each center. Example: the typical sector within the Salt Lake Center is forecast to service 0.313 general aviation aircraft per minute per 100 square miles in 1985, and 0.085 air carrier and military vehicles. From this base one can show that the Salt Lake Center will have under surveillance some 1446 aircraft at any one time: 1139 GA vehicles and 307 air carrier and military aircraft.

The forecast activity for each of the six centers considered was evaluated in a similar way, the worst case being Kansas City with 9001 vehicles, 8544 GA and 457 air carrier and military aircraft, forecast to be under surveillance during a peak minute activity period.

Busy hour operations were evaluated for three major terminal areas in an effort to gain insight to forecast growth rates, distribution of GA to air carrier operations, and the ratio of VFR to IFR operations. The results are summarized in Table III, page 1-6.

The general aviation and air carrier navigation performance requirements are summarized in Table IV. They were calculated from an evaluation of the following three arguments.

(1) 1985 peak minute density (overs, departures and arrivals) per 100 square nmi.

(2) 1985 peak minute density (overs, departures and arrivals) under surveillance per ATC center.

(3) 1980 peak hour operations (arrivals, departures) within a Large Hub.

TABLE I

TYPICAL CENTER - 1985 TRAFFIC ACTIVITY FORECAST

Typical Center	Typical Sector Type (GA Low Med High)	Av. Sector Area sq miles	# of 100 sq. mi. Units	Peak Minute General Aviation Traffic	Peak Minute Air Carrier & Military Traffic	Peak Minute GA under Center Surveillance	Peak Minute Air Carrier & Military under Center Surveillance
Salt Lake Center	Low GA High Altitude Through	17,300	173	0 313	0 085	1139	307
Oakland Center	Low GA Transitioning	1,170	11	6 2	1 02	2449	406
Oakland Center	Low GA Low Altitude Through	15,750	188	0 384	0 06	-	-
Kansas City Center	Med GA High Altitude Through	18,200	182	1 68	0 083	8544	412
Kansas City Center	Med GA Transitioning	7,800	78	3 92	0 19	-	-
Houston Center	Med GA Low Altitude Through	9,700	97	0 80	0 08	3034	303
Chicago Center	High GA Transitioning	770	7 7	17	1 4	5382	454
Cleveland Center	High GA Low Altitude Through	3,400	34	4 2	0 40	4860	457

TABLE II

SUMMARY OF 1985 TRAFFIC ACTIVITY FORECASTS

Average 1985 Peak Minute GA Aircraft Under Center Surveillance	Average 1985 Peak Minute Military & Air Carrier Under Center Surveillance	Average 1985 Peak Minute GA Spread per 100 nmi^2	Average 1985 Peak Minute Military & Air Carrier Spread per 100 nmi^2	1985 Peak Hour General Aviation Hub Activity	1985 Peak Hour Military & Air Carrier Hub Activity
1139-8544	303-457	0 3-17	0 06-1.4	913-5985	66-502

TABLE III

BUSY HOUR OPERATIONS EXTRAPOLATED INTO AIRCRAFT MIX 1965-1985

Forecast Factor		Highest Activity New York					Moderate Activity Detroit					Minimum Activity Cincinnati				
		1965	1970	1975	1980	1985	1965	1970	1975	1980	1985	1965	1970	1975	1980	1985
Busy Hour Operations	Air Carrier	176	213	277	372	502	40	41	57	69	81	20	27	37	50	66
	GA	1130	1962	2923	4365	5985	408	681	1035	1607	2519	194	249	389	611	913
Air Carrier	A	67	83	107	133	161	10	13	16	18	20	4	7	10	11	12
	B	109	130	170	239	341	30	28	41	51	61	16	20	27	39	54
General Aviation	GA3(C)	7	79	199	360	556	2	30	77	145	236	1	6	16	32	53
	GA1 GA2 (D-E)	1123	1880	2724	4005	5429	406	651	958	1462	2283	193	243	373	579	860
General Aviation to Air Carrier Ratio	GA1, GA2, GA3, Air Carrier	1				12/1	1				31/1	1			18/1	14/1
Air Carrier Growth	GA3, Air Carrier	1				3/1	1				2/1	1			2 5/1	3 3/1
GA Growth	GA1, GA2	1				5/1	1				6/1	1			3/1	4 7/1

The navigation requirements are:

- General aviation GA1, GA2

  σ_{AT} = 1.5 nmi, 5 minutes

  σ_{CT} = 0.2 to 1.0 nmi

- Military and Air Carrier (low altitude)

  σ_{AT} = 2.5 nmi, 5 minutes

  σ_{CT} = 0.5 - 5 nmi

- Military and Air Carrier (high altitude)

  σ_{AT} = 5.0 nmi, 15 minutes

  σ_{CT} = 0.5 - 6 nmi

TABLE IV.
NAVIGATION ACCURACY REQUIREMENTS - TRAFFIC ACTIVITY FORECASTS

Activity Forecast	General Aviation GA1, GA2			Military and Air Carrier GA3, CTOL, VTOL, STOL					
	Altitude: 6 kft - 11 kft			Altitude 11 kft - 18 kft			Altitude 18 kft - 39 kft		
** → 3 σ values	σ_{CT} nmi	σ_{AT} nmi	σ_{AT} min.*	σ_{CT} nmi	σ_{AT} nmi	σ_{AT} min.	σ_{CT} nmi	σ_{AT} nmi	σ_{AT} min.
Peak Minute Density per 100 sq. nmi	0.3-1.0	1.5	5.0	0.4	2.5	5.0	1.0	5.0	15
Peak Minute Density per center (arrivals, departures, overs)	0.14-0.45	1.5	5.0	0.6-0.8	2.5	5.0	0.4-0.7	5.0	15
Peak Hour Density per Hub (arrivals, departures, overs)	0.18-0.83	1.5	5.0	0.7-5.0	2.5	5.0	0.5-6.0	5.0	15
Nominal Range Summary	0.2-1.0	1.5	5.0	0.5-5	2.5	5.0	0.5-6.0	5.0	15

*minutes

1.2 CATEGORIES OF USERS

The Users of the proposed advanced navigation traffic control system were assumed to consist of three categories of general aviation aircraft and four categories of commercial carriers. Typical aircraft forecast to be operational during the 1975 to 1985 time frame were used as design point vehicles in order to develop representative flight profiles; to develop an appreciation of significant differences in performance characteristics, such as cruise speed, rate of climb, minimum approach speed, etc; and to provide the information necessary to modeling the geometry of the aircraft flight profiles for purposes of conflict prediction.

1.2.1 Kinds of Aircraft

Table V summarizes the aircraft selected for evaluation in this study. The Mach 2.0 cruise speed Concorde was selected as the candidate SST, and the Mach 0.8 cruise speed DC-8 as the representative CTOL jet. Both of these aircraft were configured for the typical transcontinental or trans-ocean non-stop flight, termed "long haul". Two types of VTOL aircraft were considered: a turbo-prop tilt-wing aircraft and a turbofan vehicle for use on the 200 to 500 nmi short haul air carrier mission. The mission of less than 200 nmi was classed as an air-taxi operation in which the helicopter was used as the candidate vehicle. The STOL aircraft selected for evaluation was a turbo-prop aircraft.

The general aviation aircraft were subdivided into three categories, GAI, GA2 and GA3. This subdivision was used to differentiate between the professional pilot who typically flys a corporate jet aircraft, GA 3, and the non-professional, and sometimes marginally proficient, pilot who flys small reciprocating-engined aircraft. Within this latter set, two further divisions were made: GA I was used to describe the small aircraft equipped with minimal avionics gear; GA 2 is typified by the $45,000 price range, well-equipped, single engine craft with retractable landing gear, or small twin engined, privately-owned aircraft. Note: military aircraft were not considered in this study beyond accounting for their impact on traffic forecasts.

Generally, the GA aircraft were considered to possess avionics equipment which is distinctly separable into two levels of performance, primarily as a function of cost. Pilot performance was also assumed to be divisible into two categories, professional and non-professional. The latter category implies fewer flying hours per year, less training, and greater vulnerability to workload increases from factors external to the aircraft.

The V/STOL aircraft vehicles selected for evaluation were:

(1) Turbo prop, tilt wing VTOL typified by the XC-142

(2) Lift fan VTOL typified by the XV-5A

(3) Turbo prop STOL, typified by the Breguet 941/McDonnell 188E

TABLE V
USERS OF THE ADVANCED NAVIGATION/TRAFFIC CONTROL SYSTEM

FACTOR	VTOL			STOL		GA			CTOL Jet	SST
	Turbo prop Tilt wing	Lift Fan	Heli-copter	Turbo Jet	Turbo prop	GA 1*	GA 2**	GA 3		
Aircraft Type or Forerunner	XC-142	XV-5A	H-47	CTOL Jet	Breguet 941	Cessna 150 & 172	Beech Bonanza & Piper Navajo	Jet Star	DC-8	Concorde
Range (nm)	435	435	200	435	435	380	800	1800	4500	3400
Cruise Speed) (KTAS)	355 (425)***	435 (485)	155	435 (450)	340 (340)	95	210	445	480	1175 (M-2)
Cruise Altitude (1000 ft)	30 (5)***	30 (5)	10	30 (10)	25 (5)	6	9	35	35	57
Climb Speed (KTAS)	260	400		208		70	120	270	270-490	525-1030
Climb Rate (fpm)	1000-4000	1000-4700	1700	1000-2500		500	1000	2000-3500	3000	1000-7000
Descent Rate (fpm)	1000-3000	1000-3800	1000	1000-3000		500	500-1000	500-6000	2000	1000-10,000
Descent Speed (KTAS)	450	410		435		70	85	125	315-256	1100-345
VMC Approach Slope (deg)	3-12	3-12		3-11	3-11	7	7	3	3	3

* Equipped for VFR only
** Equipped for IFR, but predominately VFR operational
*** Parentheses indicate 174 nmi stage length

These aircraft are designed to operate profitably over short range lengths. Typical are the 100, 300, up to 500 nmi stage lengths between city pairs in the California Corridor, and the 405 nmi stage between Boston and Washington. These potentially short stage lengths imply a dependence on a good vertical navigation capability and an inherently high communications workload.

1.2.2 Cruise Conditions

The cruise true air speed/altitude performance envelope is shown in Figure 2. The potential range of cruise speeds over the design altitude regime of the 100-500 mile stage lengths is seen to be 380 kts to 515 kts. The cruise altitude envelope is expected to range from 25,000 to 35,000 feet; thus potential conflict with CTOL and GA aircraft dictates the use of slant tracks and a parallel track or area navigation system.

Cruise speeds of CTOL vs V/STOL aircraft will vary by as much as 50%. This potential source of conflict enroute will be duplicated in the terminal area. Evaluation of the VTOL and STOL terminal area profile indicates that approximately eleven minutes will be spent at altitudes which will be in direct conflict with general aviation and air taxi aircraft passing through the area at their respective cruising altitudes.

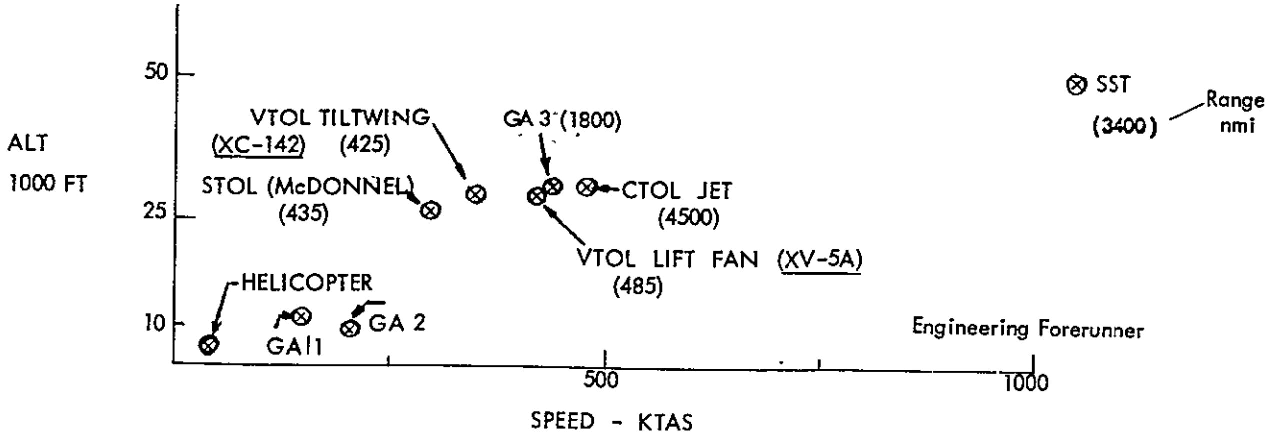


Figure 2. User Aircraft Cruise Conditions

CTOL jet aircraft cruise altitude and speeds will be in conflict with those of VTOL and STOL aircraft, thus creating a potential flow-control problem in congested airspace. During cruise the SST will generally fly above 45,000 feet, thus will not be constrained by subsonic traffic. Air taxi aircraft and general aviation aircraft, other than the turbo GA3 business aircraft, tend to cruise at altitudes of 6,000 feet to 10,000 feet, the densely populated terminal area altitude. The potential navigation/ATC solution must incorporate parallel and slant tracks, speed scheduling, path stretching, the use of RTAs (required time of arrival) and 3-d area navigation. The ATC agency will require a continuously available output from the airborne system of unambiguous, precise, blunder-free surveillance data.

1.3 USER MISSIONS AND PROFILES

Flight profiles for each type of user aircraft were constructed in sufficient detail to permit identification of the significant input variables to the system, i.e. aircraft performance, mission events, navigation and communication events, approach procedures, pilot workload, etc.

The profiles were subdivided into seven phases: taxi, take-off, climb out, cruise, descent, approach and land; evaluated in the context of both VFR and IFR flight; and evaluated as to time, altitude, speed and distance. The results of this evaluation are presented in the illustrations and tables which follow.

(1) VTOL and STOL aircraft profiles. Illustrations of the profiles for taxi, climbout, cruise, descent and approach are presented in Figures 3, 4 5 and 6. Tables VI and VII summarize the time, speed, altitude and distance relations which must be considered in the specification of a candidate navigation/air traffic control system. Attention is directed to the performance range of speed and vertical velocity of these aircraft.

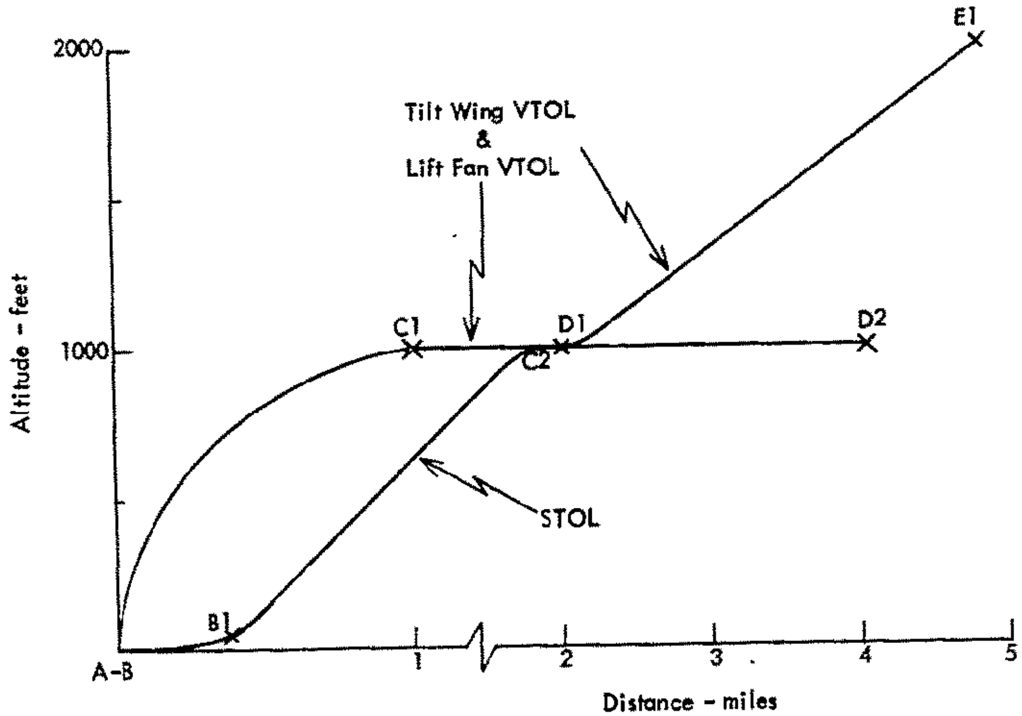


Figure 3. Taxi, Climb-Out - Nominal Mission Profile VTOL and STOL Aircraft

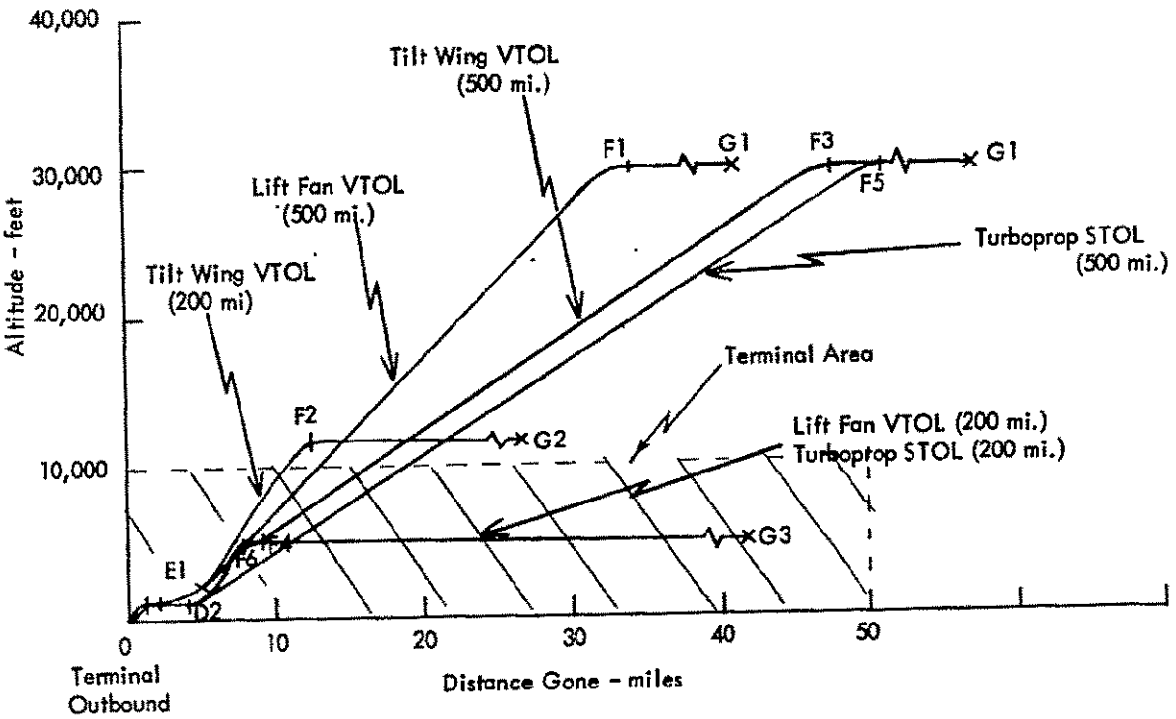


Figure 4. Climb-Out, Cruise - Nominal Mission Profile - VTOL and STOL Aircraft

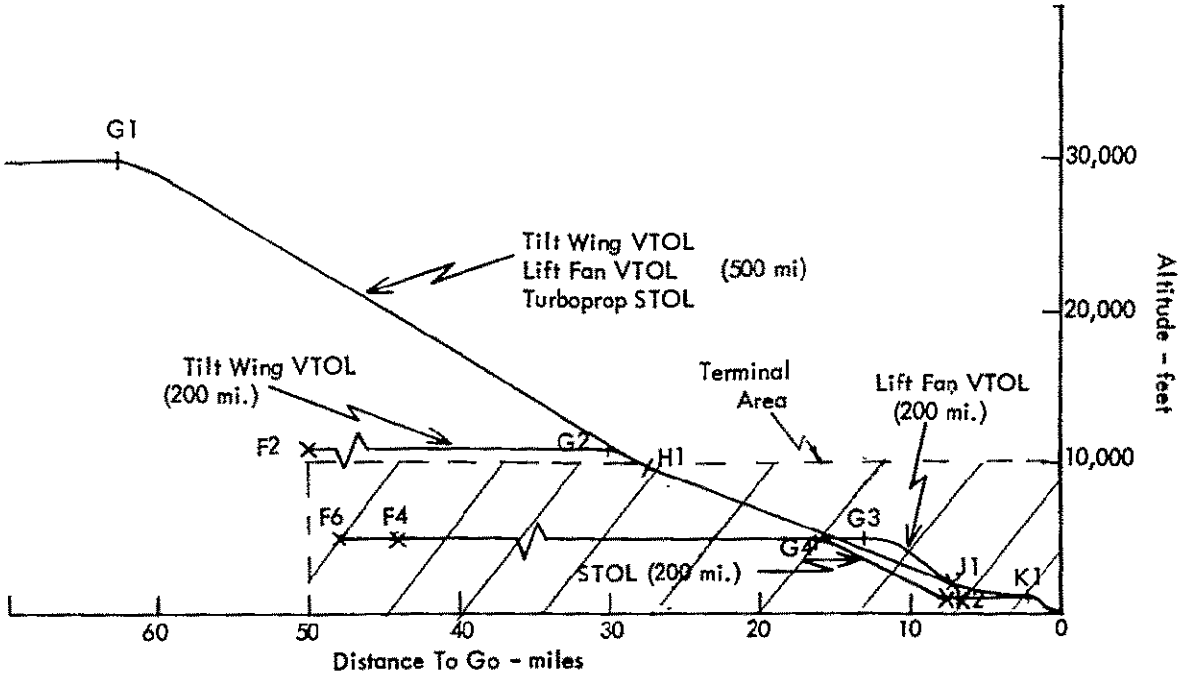


Figure 5. Enroute, Descent - Nominal Mission Profile - VTOL and STOL Aircraft.

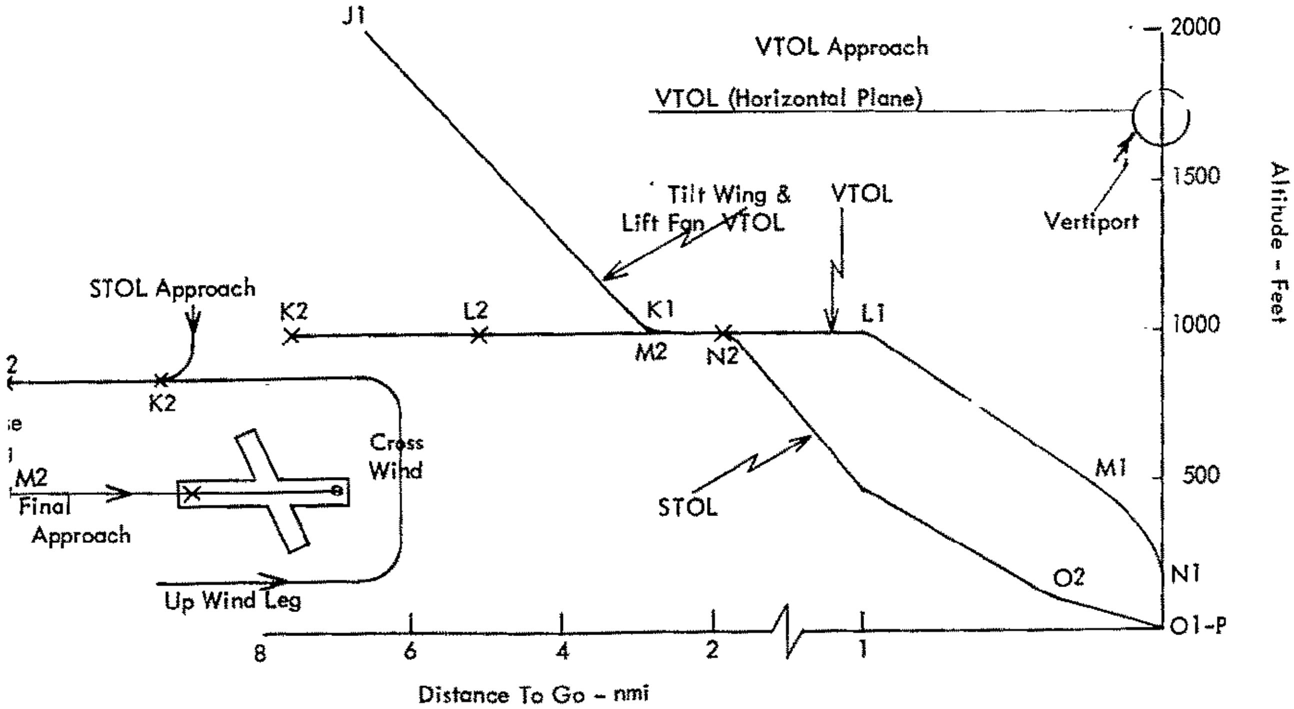


Figure 6. Final Approach and Landing - Nominal Mission Profile - VTOL and STOL Aircraft

TABLE VI
NOMINAL MISSION PROFILE VTOL TILT-WING AIRCRAFT (500-mile Stage Length)

Flight Profile Phase	Segment	Function	Time min.	Time per Event min.	*Average TAS (kts)	Average Vertical Rate, fpm	Flight Path Angle, deg.	Total Dist. Travelled miles	Altitude, ft. (Avg.)
Taxi Out	A-B		0.0	1.5	8			350 ft.	
Take Off1	B-C1	Clear to 1000 ft. MOCA	1.5	2.5	172(C1)	1000	90-0.0	1.0	1,000
Climb Out2	C1-D1	Accelerate for climb	2.5	0.2	200 230(D)	0.0		2.0	1,000
	D1-E1	Conversion	2.7	1.0	230	1000	3	4.8	2,000
Climb Out	E1-F1		3.7	10.7	300	4000	7	34	30,000
Enroute Cruise	F1-G1		65.7	55.0	440	0.0	0.0	438	30,000
Descent	G1-H1		61.6	6.6	440	3000	-7	473	10,000
	H1-J1	ATC	68.2	5.3	290	1500	-3	493	2,000
	J1-K1	Conversion	73.5	3.8	230 172(K1)	1000	-3	497	1,000
Final Approach	K1-L1	Align to ILS Localizer	77.3	0.8	161 150(L1)	0	0	499	1,000
	L1-M1	Align to Glide Slope	78.1	0.3	140 130(M1)	1200	-11	499	500
Land	M1-N1	Kill TAS	78.4	0.3	0(N1)	500	90°	500	200
	N1-O1		78.7	0.5	0	400	90°	500	0
Taxi In	O1-P		79 2	1.5	8			350 ft.	

1 vertical acceleration 0 1g, horizontal 0.15g

2 horizontal acceleration 0.25g

* Parenthesis indicates TAS at segment point

TABLE VII
NOMINAL MISSION PROFILE, STOL AIRCRAFT (500-mile Stage Length) (Turbojet)

Flight Profile Phase	Segment	Function	Time min.	Time per Event min.	Average TAS (kts)	Average Vertical Rate, fpm	Flight Path Angle deg.	Total Dist. Travelled miles	(Avg.) Altitude, ft.
Taxi Out	A-B		0.0	3.0	10			2500 ft.	
Take Off	B-C2	Clear to 1000 ft MOCA	3.0	0.3	92(B1) 138(C2)	3000	7	1.9	1,000
Climb Out	C2-D2	Accelerate to Climb Speed	3.3	0.8	180 223(C2)	0.0	0.0	4.0	1,000
	D2-F5	Attain Cruise Alt.	4.1	11.5	240	2500	6	51	30,000
Enroute Cruise	F5-G1		15.6	51.6	450	0.0	0.0	438	30,000
Descent	G1-H1		67.2	6.6	450	3000	-7	472	10,000
	H1-J1		73.8	5.3	290	1500	-3	497	2,000
	J1-K2		79.1	3 8	230 172(K1)	1000	-3	499	1,000
Approach	K2-L2	Down wind Leg	82.9	1.0	155 138(L2)	0.0	0.0	501.5	1,000
	L2-M2		83.9	1.0	120 103(M2)	0.0	0.0	503.5	1,000
Final Approach	M2-N2	Align Localizer	84.9	0.6	103	0.0	0.0	505.5	1,000
	N2-O2	Align GS	85.5	1.3	75	720	-6	507	100
Land	O2-O1		86.8	0.3	75	0.0	-3	507.2	0.0
Taxi In	O1-P		87.1	3.0	10	-			

(2) GA and CTOL jet aircraft profiles. The performance differences between GA1 and GA2 are illustrated in Figure 7, Nominal VFR Horizontal Mission Profiles. In Figure 8, the vertical profiles are combined with flight paths for GA3 and CTOL jet in order to dramatize the conflict problem in the terminal area. The significant surveillance and navigation-related data are tabulated in Tables VIII - IX.

(3) SST Climb and Descent profiles. The zones of potential conflict between SST and other users of the airspace, except for occasional military aircraft, lie in the region below 42,000 feet, the climb-out and descent phases of flight. Figure 9 illustrates these events while Table XII summarizes the relevant performance data.

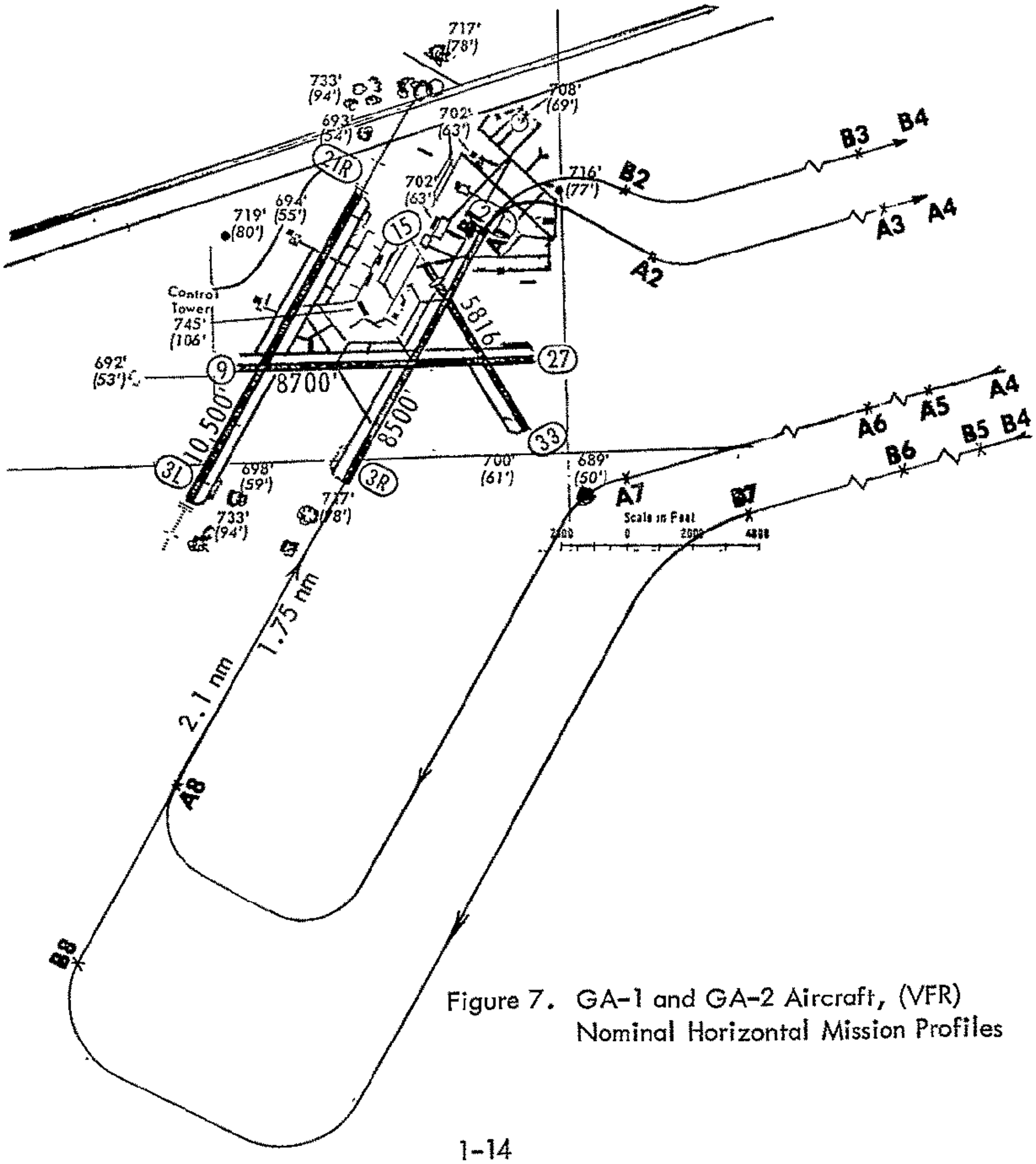


Figure 7. GA-1 and GA-2 Aircraft, (VFR) Nominal Horizontal Mission Profiles

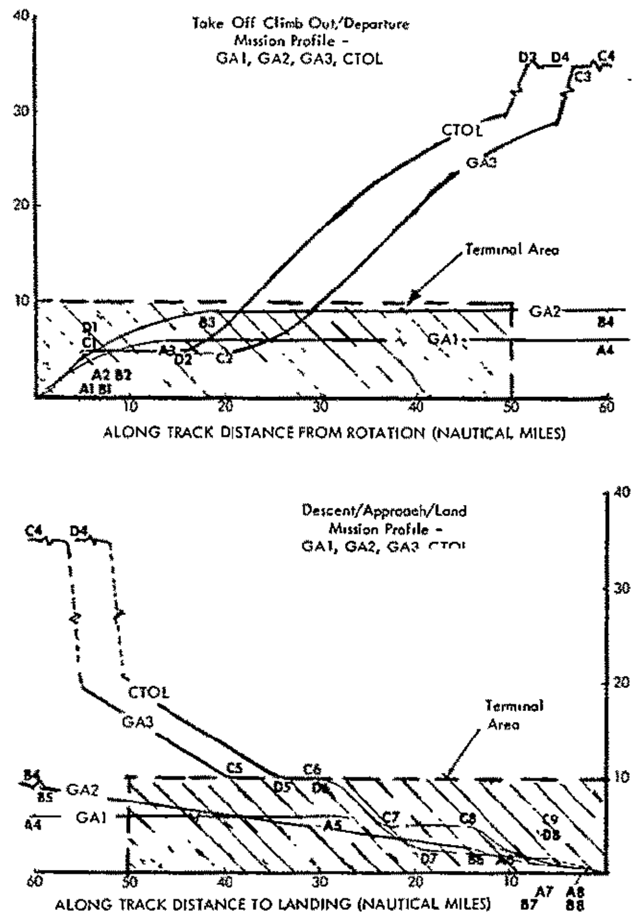


Figure 8. GA1, GA2, GA3 and CTOL Aircraft, Nominal Vertical Mission Profiles

TABLE VIII
GA1 AIRCRAFT FLIGHT PROFILE DATA

Flight Profile Phase	Segment	Function	Time min.	Time per Event min.	Average TAS (kts)	Average Vertical Rate, fpm	Flt Path Angle deg.	Total Dist. Travelled nm*	Altitude ft. (Average)
Take Off	0-A1		0.0	1	70	500	4	1.2	500
Climb	A1-A2		1.0	0.7	70	714	6	2.0	1000
Climb	A2-A3	Depart Pattern	1.7	10.3	70	485	4	14.0	6000
Climb	A3-A4-A5		12.0	148.5	95	0	0	-28.8	6000
Descent	A5-A6		160.5	11.7	95	500	-2	-10.3	2500
Descent	A6-A7	Enter Pattern	172.2	3.0	95	462	-3	- 5.8	1000
Approach	A7-A8		175.2	3.3	70	333	-1	- 1.8	500
	A8-Lan		178.5	1.5					0

TABLE IX
GA2 AIRCRAFT FLIGHT PROFILE DATA

Flight Profile Phase	Segment	Function	Time min.	Time per Event min.	Average TAS (kts)	Average Vertical Rate, fpm	Flight Path Angle deg.	Total Dist. Travelled nm*	Altitude ft. (Average)
Take Off	0-B1		0.0	0.5	120	1000	4	1.2	500
Climb	B1-B2		0.5	0.5	120	1000	6	2.0	1000
Climb	B2-B3	Depart Pattern	1.0	8.0	120	1000	5	18.0	9000
Cruise	B3-B4-B5		9.0	150.7	210	0	0	-59.0	9000
Descend	B5-B6		159.7	13.0	210	500	-1	-13.5	2500
Descend	B6-B7	Enter Pattern	172.7	3.0	120	500	-2	-7.5	1000
Approach	B7-B8		175.7	2.6	120	333	-1	-2.1	500
Final	B8-Land		178.5	1.5					0

* Positive value indicates distance gone, while minus sign denotes distance to go to touchdown.

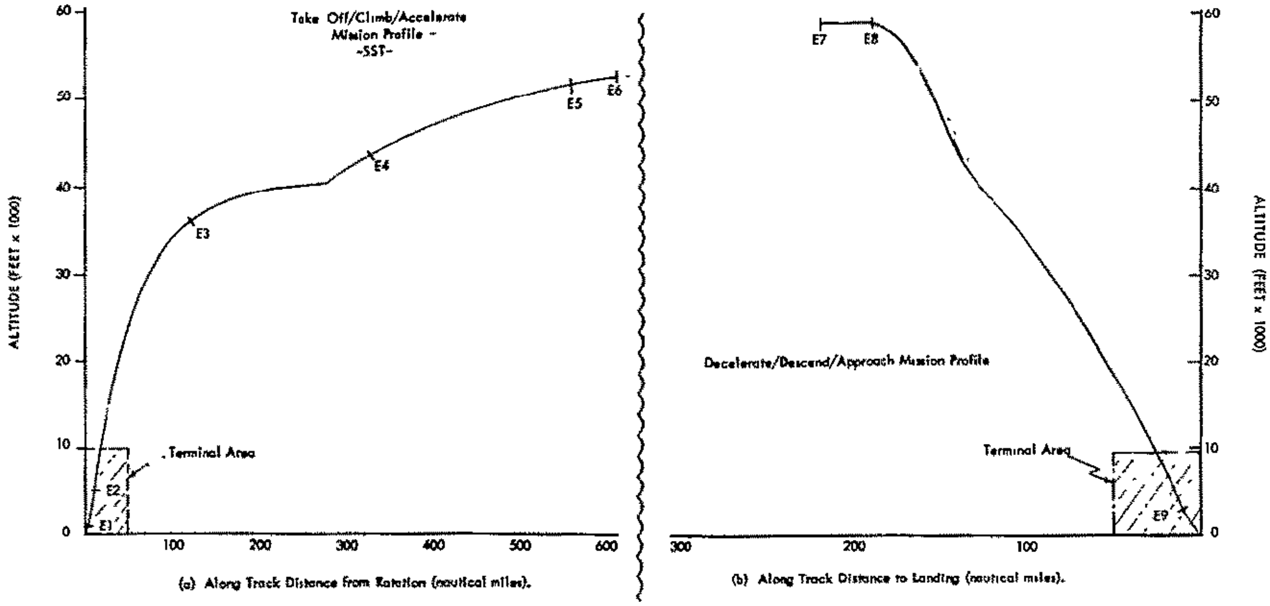
TABLE X
GA3 AIRCRAFT FLIGHT PROFILE DATA

Flight Profile Phase	Segment	Function	Time min	Time per Event min.	Average TAS (kts)	Average Vertical Rate, fpm	Flight Path Angle deg	Total Dist. Travelled nm*	Altitude ft. (Average)
Take Off	0-C1		0.0	1.5	250	3333	8	6.3	5000
Level	C1-C2	ATC Handoff	1.5	3.3	250	0	0	20.0	5000
Climb	C2-C3		4.8	12.0	250 at alt. ≤ 10k ft 270 at alt. > 10k ft	2500	5	74.0	35000
Cruise	C3-C4		16.8	146.2	445	0	0	-80.2	35000
Descend	C4-C5		163.0	5.5	445	4500	-6	-39.0	10000
Level	C5-C6		168.5	2.0	250	0	0	-30.8	10000
Descend	C6-C7		170.5	2.0	250	2500	-6	-22.5	5000
Level	C7-C8	ATC Handoff	172.5	2.0	250	0	0	-14.3	5000
Descend	C8-C9	Acquire ILS & GS	174.5	1.5	250	835	-5	-8.0	1661
Final	C9-Land		176.0	4.0			-3		0

TABLE XI
CTOL AIRCRAFT FLIGHT PROFILE DATA

Flight Profile Phase	Segment	Function	Time min.	Time per Event min.	Average TAS (kts)	Average Vertical Rate, fpm	Flight Path Angle deg.	Total Dist Travelled nm*	Altitude ft. (Average)
Take Off	0-D1		0.0	1.5	250	3333	8	6.3	5000
Level	D1-D2		1.5	2.3	250	0	0	15.7	5000
Climb	D2-		3.8	1.7	250	3012	7	22.5	10000
Climb	-D3		5.5	8.3	400	3000	4	78.0	35000
Cruise	D3-D4		13.8	91.9	480	0	0	-74.3	35000
Descend	D4-D5		105.7	5.0	480	5000	-6	-34.3	10000
Level	D5-D6		110.7	1.0	250	0	0	-30.1	10000
Descend	D6-D7	ATC Handoff	111.7	3.0	250	2500	-6	-18.6	2500
Descend	D7-D8	Acquire ILS & GS	114.7	2.5	250	300	-1	-8.0	1661
Final	D8-Land		117.2	2.8			-3		0

* Positive value indicates distance gone, while minus sign denotes distance to go to touchdown.



Climb-Out

Descent

Figure 9. SST Aircraft, Nominal Vertical Mission Profile

TABLE XII
SST AIRCRAFT FLIGHT PROFILE DATA

Flight Profile Phase	Segment	Function	Start CAS (kts)	End CAS (kts)	Start GS (kts)	End GS (kts)	Avg. GS (kts)	Total Dist. (nmi)	Climb Rate (fpm)	Avg. Climb Rate (fpm)	Flight Path Angle (deg)	End Altitude (ft)	Time per Event (min)	Time (min)	Dist. (nmi)
Take Off & Accel.	0-E1	Rotation to 1000 ft	200	240	200	240	220	4	0	1000	≈6.3	1000	1.0	1.0	4
Climb-1	E1-E2	Accelerate to 400 KCAS	240	400	240	430	300	11	1000	2860	5.7	5000	1.4	2.4	11
Climb-2	E2-E3	Climb constant CAS	400	400	430	760	572	119	2860	2740	2.9	36000	11.3	13.7	119
Climb-3	E3-E4	$\dot{h}^{\circ}/\dot{V}^{\circ}$ schedule to 530 KCAS	400	530	760	1000	775	329	2740	475	0.3	43750	16.3	30 0	329
Climb-4	E4-E5	Constant CAS to M 2.05	530	530	1000	1165	1120	559	475	660	0.2	51500	12.3	42.2	559
Climb-5	E5-E6	M 2.05 to RoC ≤ 200 fpm	530	520	1165	1165	1165	609	660	200	0.09	52300	2.5	44.7	609
Cruise	E6-E7	Cruise to start of decel.	520	450	1165	1165	1165	3029	200	≤ 50	0.02	59000	124.0	208.7	-220
Decel./ Descent-1	E7-E8	Decelerate to 325 KCAS	450	325	1165	870	900	3059	-	-	0	59000	2.0	210.7	-190
Decel./ Descent-2	E8-E9	Descend to 3000 ft	325	325	870	330	500	3239	0	-2400	-5	3000	21.5	232.2	-10
Approach & Land	E9-Land		325	140	325	140	240	3249	0	-1200	-3	0	2.5	234.7	0

* Positive value indicates distance gone, while minus sign denotes distance to go to touchdown.

1.4 USER SYBSYSTEMS - INITIAL CONFIGURATIONS

Assessment of navigation, communication and workload criteria required that some initial configuration of avionic subsystems be postulated. Table XIII summarizes these first configurations used in the study.

TABLE XIII
AIRBORNE NAVIGATION SYSTEM INSTALLATIONS

All include pilotage

USER		POSITION FIX	DEAD RECKONING			HOMING	ATTITUDE & HEADING	TO, APPROACH & LANDING
			Horizontal	Vertical	Heading			
General Aviation	GA 1	map read charts VOR	Air Data	Pressure Altimeter	Mag Compass	Comm/Nav 90 channel VHF VOR, LOC	Mag Compass AI	Comm/Nav R/T 90 Channel (LOC)
	GA 2	map read charts VOR	Air Data	Pressure Altimeter	Mag Compass	Comm/Nav VHF VOR/LOC,ADF	AI, Mag Compass	Comm/Nav R/T 360 Channel MBR, ADF, LOC
	GA 3	VOR/DME map read	Air Data Doppler	Pressure Altimeter Radar Alt.	Compass Mag/DG	Comm/Nav, VOR LOC, ADF	Mag Compass ADI, Vertical Gyro	Comm/Nav R/T 360 Channel MBR ADF, DME,LOC, GS
CTOL Jet	Long Haul	Loran A/C celestial map read VOR/DME	INS(2), Air Data Doppler	Pressure Altimeter Radar Altimeter	Compass Mag/DG	Comm/Nav VHF R/T (VOR, LOC) ADF	Attitude Reference Unit	Comm/Nav Transceiver, ILS (LOC, GS) DME,MBR, ADF
	Short Haul	VOR/DME	Air Data	"	"	"	"	"
VTOL	Helicopter	Decca Hyperbolic VOR/DME map read	Doppler Air Data	Radar Altimeter, Doppler Radar	Mag Compass	Comm/Nav VHF R/T (VOR,LOC) ADF	Vertical Gyro	
	Tilt Wing/ Lift Fan	VOR/DME map read	Air Data	Pressure Altimeter Radar Altimeter	ARU Mag Compass	Comm/Nav VHF R/T (VOR, LOC) ADF	Mag Compass Attitude Reference Unit	Comm/Nav Transceiver, ILS (LOC, GS),DME,MBR, ADF
STOL	Turbo prop	"	Air Data	"	Mag Compass Gyro	"	"	"
	Turbo fan	"	Air Data	"	"	"	"	"
SST		map read NAV SAT VOR/DME Loran C	INS(2), Air Data	INS,Radar Altimeter Pressure Alt	INS, Mag Compass	(VOR, LOC) Comm/Nav R/T	IRU Mag Compass	AILS,DME,INS

1.5 GENERAL INFORMATION REQUIREMENTS

A summary of cockpit information needs is presented below.. These are discussed more fully in Section 3, Vol II, and Appendix B, Vol III. Consideration of this data and its impact on communications and navigation management was necessary in the development of the workload models. The tabulations appearing on Pages 1-21 and 1-22 describe one set, Situation Information, which is of concern in the specification of a navigation system.

1. Aircraft State - Primary consideration is to know the basic elements of information which affect the aircraft's ability to take off, to cruise and to land safely. These will include at least: minimum airspeed, attitude, vertical velocity, and fuel remaining.

2. Hazard Avoidance - To safely manage the aircraft's flight path requires knowledge of airfield runway situation, presence of high ground, presence of turbulence, location of obstacles, and proximity to other aircraft.

3. Command Information - To efficiently and safely control the aircraft flight path requires knowledge of steering error, error in expected time of arrival, relationship to command speed, start of climb and descent points, and error in vertical positions and rate.

4. Situation Information - To make valid judgements regarding future action it is necessary to know present track, speed, altitude, vertical velocity, present time, aircraft position, and any error in position.

5. Systems Status - The pilot must be able to monitor and control operational status of all subsystems of the navigation/communication/control system complex.

6. Environmental Situation - Significant flight path variables are influenced by ambient temperature, wind direction and velocity, atmospheric pressure, density altitude, and natural hazards (e.g., ice, restrictions to visibility and turbulence).

7. Special Navigation Procedures - Air crew must have the capability to cope with a variety of special procedures involving computation, analysis and judgement (e.g. alternate routing procedures, slant tracks, point of no return, ADIZ boundaries, notices to airmen, control time maneuvers, etc.).

8. Special Operational Procedures - These include the capability to comply with special noise abatement procedures during takeoff and climb out, sonic boom minimization criteria, and speed and noise restrictions imposed during the approach and landing phase.

9. ATC-Related Control Information - The conflict avoidance task requires information about radius of turn, rate of closure, passenger 'g' limits, proximity to other aircraft, intentions of aircraft approaching a conflict situation, terminal situation at expected time of arrival, and path stretching and speed control capabilities.

10. Communications - Navigation/ATC Related - The primary NAV-ATC related communications capabilities of significance in the information set, relate primarily to the ability to request, receive, revise, acknowledge, and evaluate a clearance.

11. Aeronautical Data - The air crew member has a responsibility to be familiar with a wide range of aeronautical data which appear in the form of NOTAMS, advisories, verbal instructions, and both permanent and temporary postings on maps, charts and approach charts.

TABLE XIV
INFORMATION NEED SUMMARY - NAVIGATION FUNCTIONS

Navigation Management Function	Flight Phase		Pilot Information Need Derived from Input	Input
	Terminal	Enroute		
Review Met Forecast	X	X	wind along track component wind cross track component	G-A comm. - wind direction, wind speed, temperature, pressure, visibility
Review Current Track	X	X	desired track distance to go	ground facility - range, bearing, mag heading, flight plan
			desired track distance to go	waypoint (wpt.) - wpt. lat., wpt. long, aircraft lat., aircraft long., mag. heading, flight plan
Update Steering	X	X	track angle error	traffic control vector - drift angle, mag. heading
			track angle error	flight plan track - range, bearing to facility, drift angle, mag. heading
			track angle error	flight plan track - wpt. lat., wpt. long., aircraft lat., aircraft long., drift angle, mag. heading
Flight Path Status Check	X	X	cross track distance ground speed estimated time of arrival altitude rate altitude	elapsed time, true airspeed, along track wind, mag. heading, drift, distance to go, pressure altitude, desired track
Flight Plan Status Check	X	X	distance to go cross track distance estimated time of arrival ground speed altitude fuel remaining	flight plan, throttle setting, pressure, density, airspeed, wind along track, elapsed time, fuel capacity

TABLE XV
PILOT'S SITUATION INFORMATION REQUIREMENTS

COCKPIT INFORMATION	WHEN									PURPOSE						IS INFO						INFORMATION SOURCE - USE						
										AIRCRAFT			ATC			Re-quired		De-sired		Accu-racy	Fre-quency of Use	Aircraft						Ground
GROUP & COMPONENT ELEMENT	Pre-Flight	Taxi	Take Off, Accelerate	Climb, Depart	Cruise, En Route	Descent, Approach	Land	Roll Out, Taxi	Dock	NAV	CTR'L	MGMT.	SURVEILL.	CTR'L	ADVISE	NOW	FUTURE	NOW	FUTURE			Sensed or Measured	Computed-Man	Computed-Aid	Displayed	Retain in Aircraft	Report to ATC	Relay from ATC
5.0 SITUATION INFORMATION																												
5.1 AIRCRAFT TRACK																												
5.1.1 Magnetic Track			x	x	x	x	x			x	v g		x	x	g	o	x	g				o	x	v	v	v	x	
5.1.2 True Track			x	x	x	x	x			x	v		x	x		x	x					x		x	x	v	x	
5.1.3 Grid Track			+	+	+	+	+			+	v		+	+		+	+					+	+	v	+		+	
5.1.4 Steering Error			x	x	x	x	x			x	x					x	x					x		x	x	x		
5.2 AIRCRAFT HEADING																												
5.2.1 Magnetic Heading	x	x	x	x	x	x	x	x		x	x			x		x	x					x		o	x	v		
5.2.2 True Heading	x	x	x	x	x	x	x	x		x	x			x		x	x					x		x	x	g^3 v		
5.2.3 Grid Heading	+	+	+	+	+	+	+	+		+	+			+		+	+					+	+	+	+	g^3_s		
5.2.4 Heading Error			x	x	x	x	x			x	x			g		x	x						g	x	x	x		
5.2.5 Compass Deviation			g	x	x	x	g			x						x	x						g	+	x	x		
5.2.6 Drift Angle			x	x	x	x	x			x						x	x					o	g		x	x		
5.2.7 Mag. Variation			x	x	x	x	x			x						x	x					x			x	x		
5.3 AIRCRAFT SPEED																												
5.3.1 Indicated Air Speed			x	x	x	x	x				x					x	x					x			x	x		
5.3.2 Calibrated Air Speed			x	x	x	x	x				x					x	x					g^3_c g		o	x	o	g^3_c g	
5.3.3 True Air Speed				x	x	x				x	x	x	x	x		x	x					x		x	x		x	
5.3.4 Mach Number				o	o	o				o	o	o	o	o		o	o					o			o		o	
5.3.5 Ground Speed				x	x	x				x			x	x			x	x				x	g		x	g	o	
5.3.6 Error in Ground Speed				x	x	x				x			x	x			x	x						x	x		x	
5.4 AIRCRAFT ALTITUDE																												
5.4.1 Pressure Alt./Flight Level			x	x	x	x	x			x	x	x	x	x		x	x					x			x		x	g
5.4.2 True Altitude		x	x	x		x	x			x	x		x	x		x	x					x			x		x	g
5.4.3 Radar Altitude			o	o		o	o			o					o	o	o					o			o	o		
5.4.4 Error in Altitude			x	x	x	x	x			x	x	x	x	x		x	x						x		x	o	o	
5.4.5 Vertical Velocity			x	x	x	x	x			x	x		x	x		x	x					x			x		x	
5.4.6 Error in Vertical Velocity			o	o	o	o	o			o			o	o			o	o						o	o	v	o	
5.5 TIME																												
5.5.1 Greenwich Mean Time	x	x	x	x	x	x	x			x			x	x		o	x	s	g			x			x		x	
5.5.2 Estimated Time Arrival (Depart)		x	x	x	x	x	x			x			x	x		x	x							x	x		x	
5.5.3 Required Time Arrival (Depart.)		x	x	x	x	x	x			x			x	x			x	x							x			

TABLE XV (CONTINUED)
PILOT'S SITUATION INFORMATION REQUIREMENTS

COCKPIT INFORMATION — GROUP & COMPONENT ELEMENT	WHEN: Pre-Flight	WHEN: Taxi	WHEN: Take Off, Accelerate	WHEN: Climb, Depart	WHEN: Cruise, En Route	WHEN: Descent, Approach	WHEN: Land	WHEN: Roll Out, Taxi	WHEN: Dock	PURPOSE: AIRCRAFT NAV	PURPOSE: AIRCRAFT CTR'L	PURPOSE: AIRCRAFT MGMT.	PURPOSE: ATC SURVEILL.	PURPOSE: ATC CTR'L	PURPOSE: ATC ADVISE	IS INFO: Required NOW	IS INFO: Required FUTURE	IS INFO: Desired NOW	IS INFO: Desired FUTURE	IS INFO: Accuracy		IS INFO: Frequency of Use		SOURCE - USE: Aircraft Sensed or Measured	Aircraft Computed-Man	Aircraft Computed-Aid	Aircraft Displayed	Aircraft Retain in Aircraft	Ground Report to ATC	Ground Relay from ATC
5.5.4 Actual Time Arrival (Depart)			x	x	x	x	x			x			x	x		o	x	g								x	x		x	
5.5.5 Est. Time En Route (Time to Go)		.	x	x	x	x	x			x						o	x	g								x	x		x	
5.5.6 Error in ETA			x	x	x	x	x			x						o	x	g								x	x		x	
5.7 AIRCRAFT POSITION																														
5.7.1 Latitue/Longitude	o	o	o	o	o	o	o	o		o			o	o										o		o	o		o	
5.7.2 Range/Bearing (W/R Facility)			x	x	x	x	x	x		x			x	x		o	x	g						x		x	x		x	
5.7.3 Cross-Track Error (Distance to Go)			x	x	x	x	x	x		x			x	x			g	g								x	x		x	
5.7.4 Error in Position			x	x	x	x	x			x							x	g								x	x	x		
5.7.5 Error in Position on Glide Slope						x	x			x						x	x							x			x	x		
5.7.6 Error in Postion on Localizer						x	x			x						x	x							x			x	x		
5.8 FUEL SITUATION																														
5.8.1 Fuel Remaining	x	x	x	x	x	x	x	x		x	x	x				x	x							x			x		x	
5.8.2 Fuel Flow			x	x	x	x	x			x	x	x				o	x	g						x			x	x		
5.8.3 Fuel Required	x	x	x	x	x	x	x			x	x	x				o	x	g								x	x	g	o	

TABLE XVI
DESIRED OPERATIONAL CAPABILITY

Accurate surveillance data for all (IFR and VFR) Aircraft, in all weather conditions, in all terminal areas must be supplied to the surveillance unit.

Multiple and flexible approach paths.

Multiple access routes, direct approach and departure routes in the terminal area.

Positive communications control on voice or data link.

Refined aircraft position increases capacity cheaply.

Priority mixing of departure and arrivals is a necessary planning function.

Incorporate automation in processing the navigation data for the clerical ground tasks.

1.6 PILOT WORKLOAD ANALYSIS METHODOLOGY

The paramount consideration of the NAVTRACS study effort - the overriding criterion upon which the entire analysis was based - was the evaluation by the pilot of how he is affected by the ATC system and his means of entry into that system, namely his cockpit environment. Therefore, the focal point of this study was the analysis of pilot workload. All of the sensitivity studies and ranking criteria, as well as recommendations for future technology developments, were based on the quantitative effect that each parameter might have upon this workload. It thus becomes essential to describe the methodology utilized in this study to evaluate pilot workload.

Figure 10 illustrates the overall approach taken which culminated in analysis of the effects of varying navigation system technologies and varying levels of automation on the degree of pilot workload, both qualitative and quantitative. All of the previously defined elements in the Data Base are brought together, with the critical control tool being the Event Sequence Diagram (ESD). ESDs for an IFR Flight Plan are illustrated in Figures 11 through 19.

Event sequence diagrams relate mission events and pilot tasks with the postulated Flight Plan Reference ATC concept. The diagram divides each flight profile into eight phases: pre-flight, taxi, take off, climb out departure, enroute, arrival, approach and land, relating on a time base, the fundamental pilot tasks of control and monitor of aircraft systems, communication and navigation management. The detailed form of the tasks depends upon the particular aircraft avionics fit, the communication, navigation and identification subsystem, control display configuration, and operational procedures adopted by the crew member--i.e., the system automation. Thus, in the analysis of any combination of navigation communication, aircraft control, and monitor equipments, the event sequence diagrams can be utilized with the Flight Plan Reference ATC system.

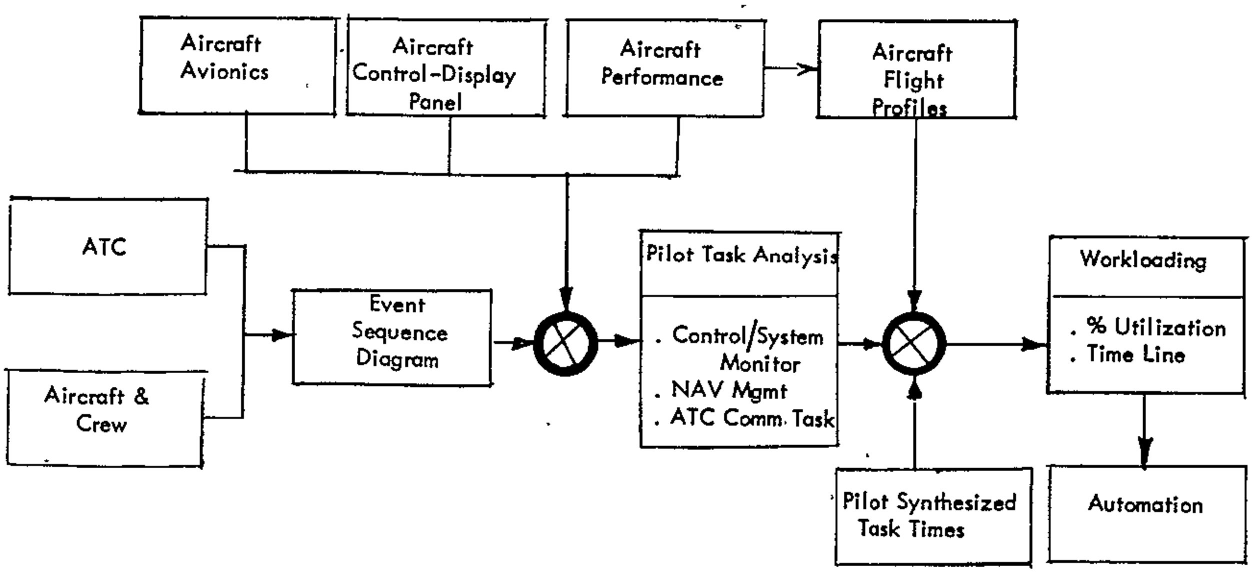


Figure 10. Pilot Workload Analysis Methodology

The VFR and IFR Event diagrams specify the mission sequence from pre-flight briefing to taxi-in and system shutdown. The diagrams identify the navigation management functions, communication management functions, and aircraft control and monitor tasks for each flight phase. They also indicate cognizant traffic control and surveillance units and show the surveillance technique employed, e.g., direct communication, Airfield Surveillance Detection Equipment (ASDE), interrogation, etc. The communication management events diagram ties together the traffic control and surveillance structure by showing both air-to-ground and ground-to-air communications.

The Event Sequence Diagrams are utilized in the pilot workload analysis in conjunction with the aircraft flight profiles developed for each user class and mission. The flight profiles provide the time base input to the ESD. The workload of the pilot (and co-pilot) of VTOL, STOL, air carrier, and general aviation aircraft, operating with a postulated set of aircraft avionics, area navigation systems, and approach and landing systems, was exercised to determine the effects of different levels of system automation. All of the analyses were performed within the frame of reference of the advanced Flight Path Reference/ATC system.

Pilot workload was computed in terms of percent utilization and total pilot execution time. During the NAVTRACS program, four essential Event Sequence Diagrams were constructed: Navigation Management Event Sequence Diagrams, VFR Event Sequence Diagrams (GA1, GA2), IFR Event Sequence Diagrams (VTOL, STOL, SST, CTOL air carriers and GA3), and All Weather Landing Event Sequence Diagrams. Only the diagrams for the IFR case are presented in Volume 1; the remaining diagrams will be found in Appendix A, Vol III.

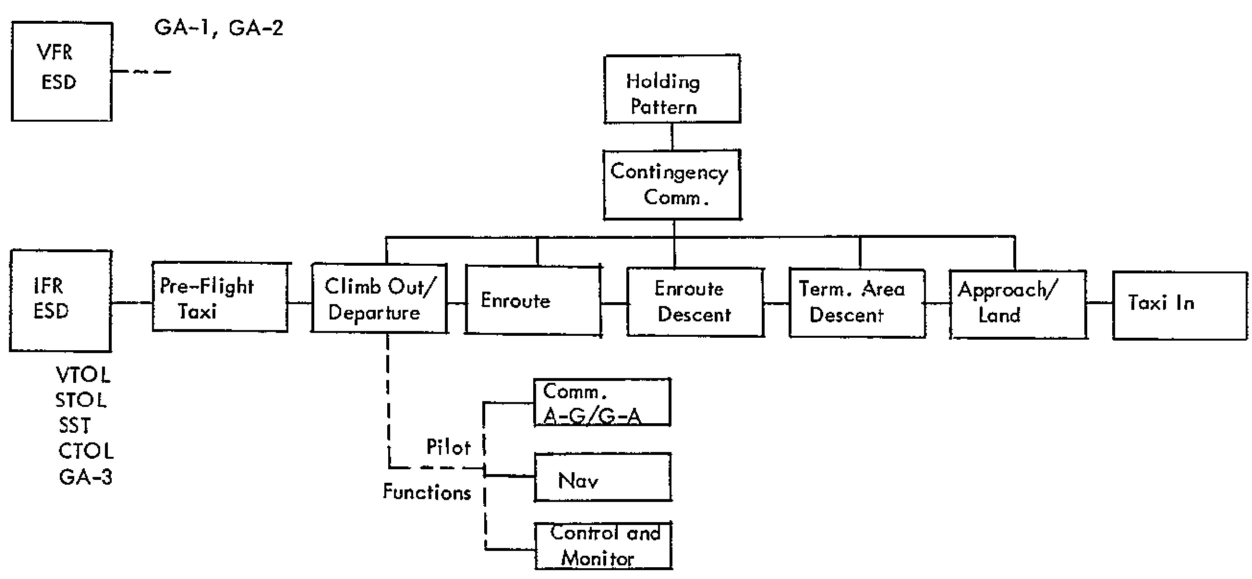


Figure 11. Organization of the Pilot/ATC Event Sequence Diagram

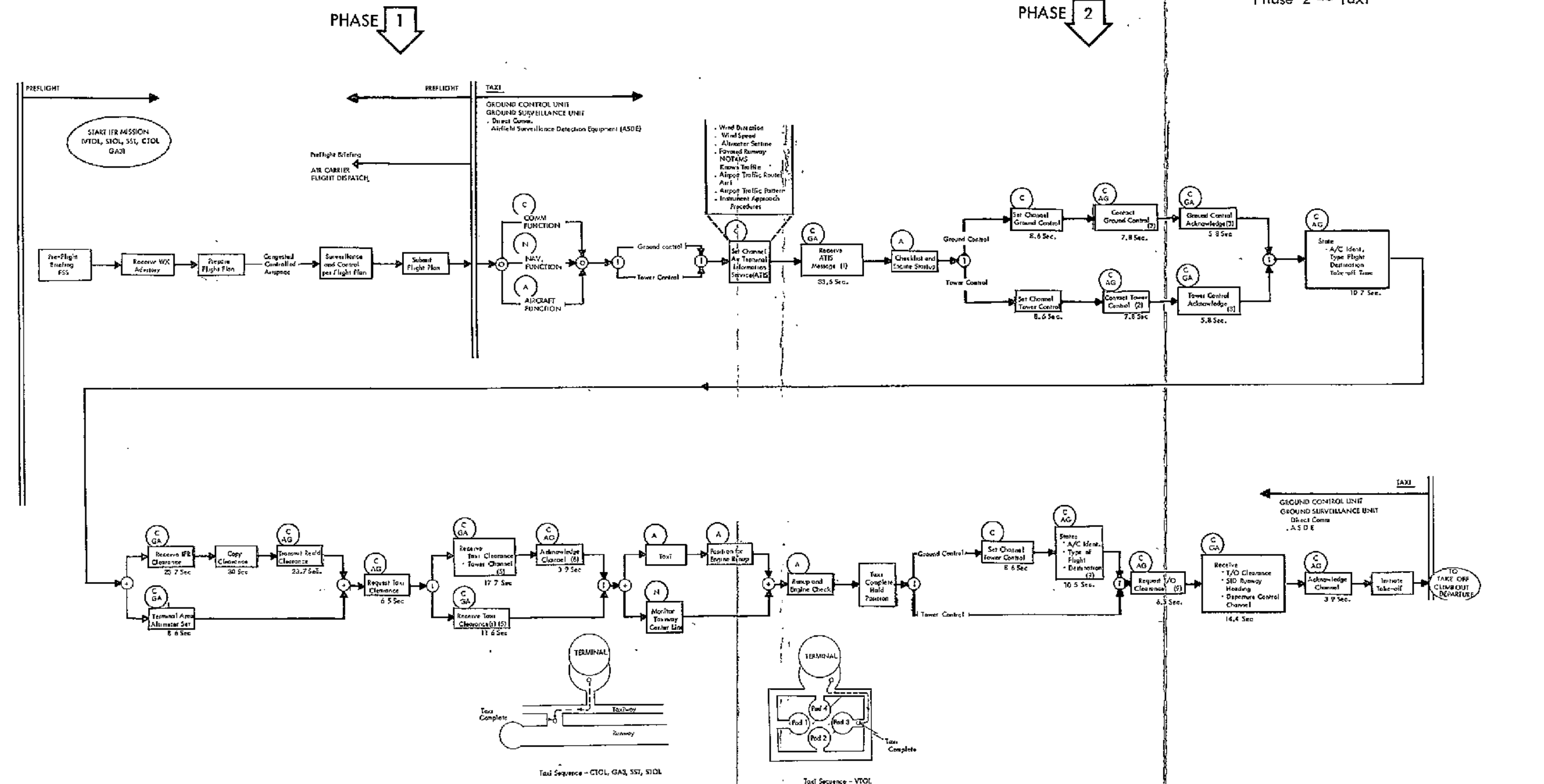
PRECEDING PAGE BLANK NOT FILMED.

EVENT SEQUENCE DIAGRAM

IFR FLIGHT PLAN

Phase 1 -- Pre-Flight

Phase 2 -- Taxi



1-27-A

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Figure 12.

EVENT SEQUENCE DIAGRAM

IFR FLIGHT PLAN

Phase 3 -- Take-Off/Climb-Out/Departure

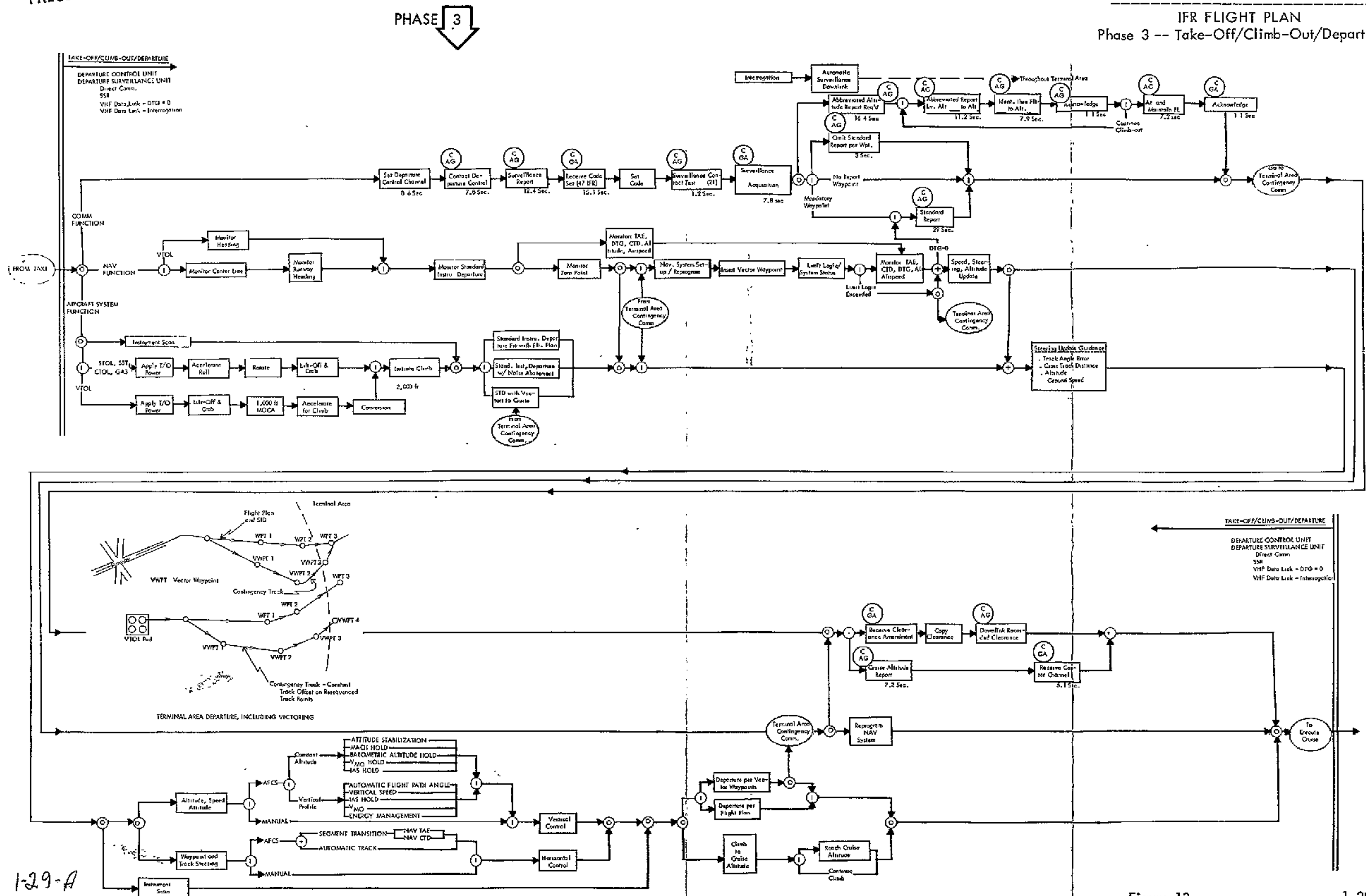
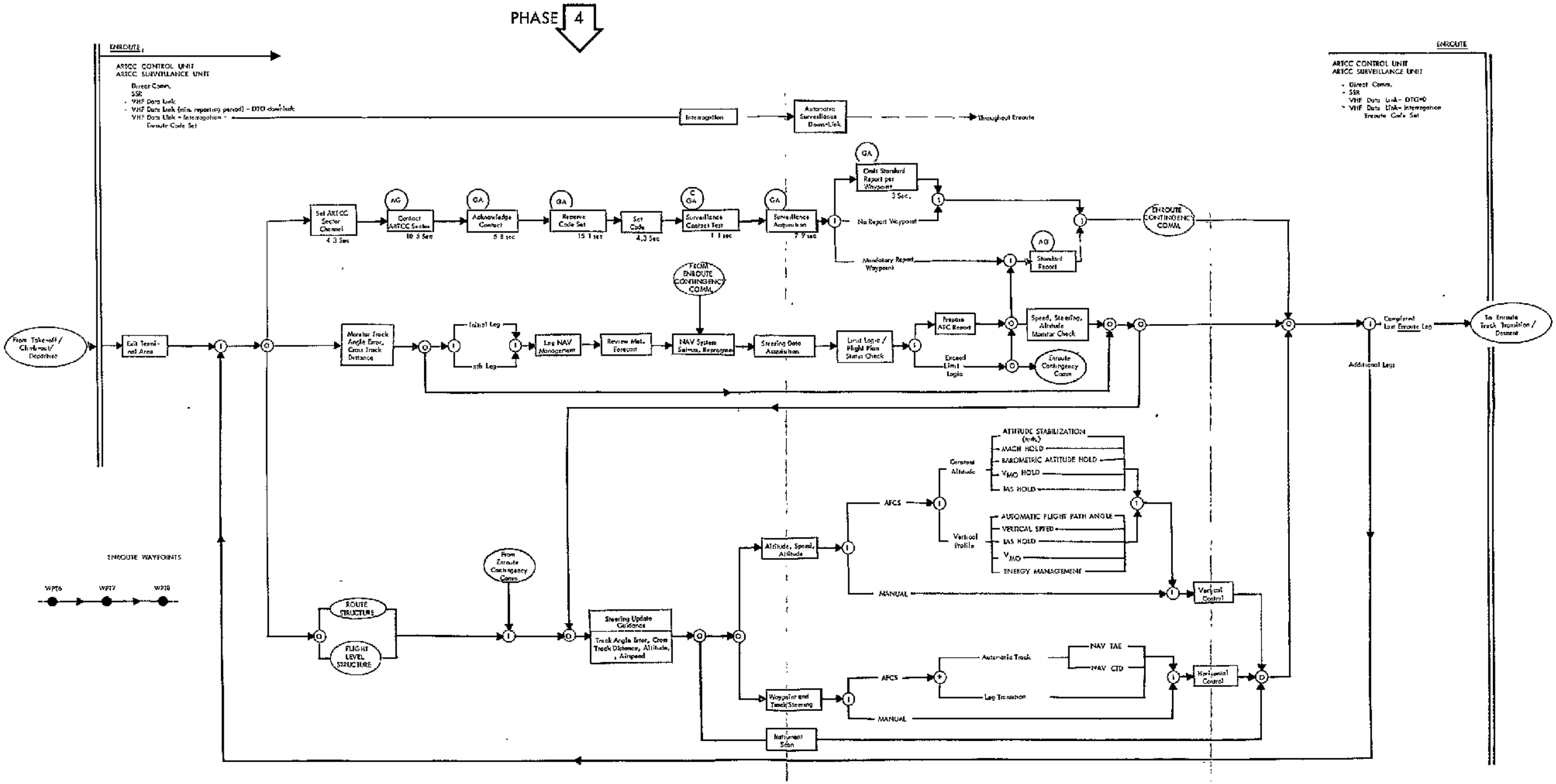


Figure 13.

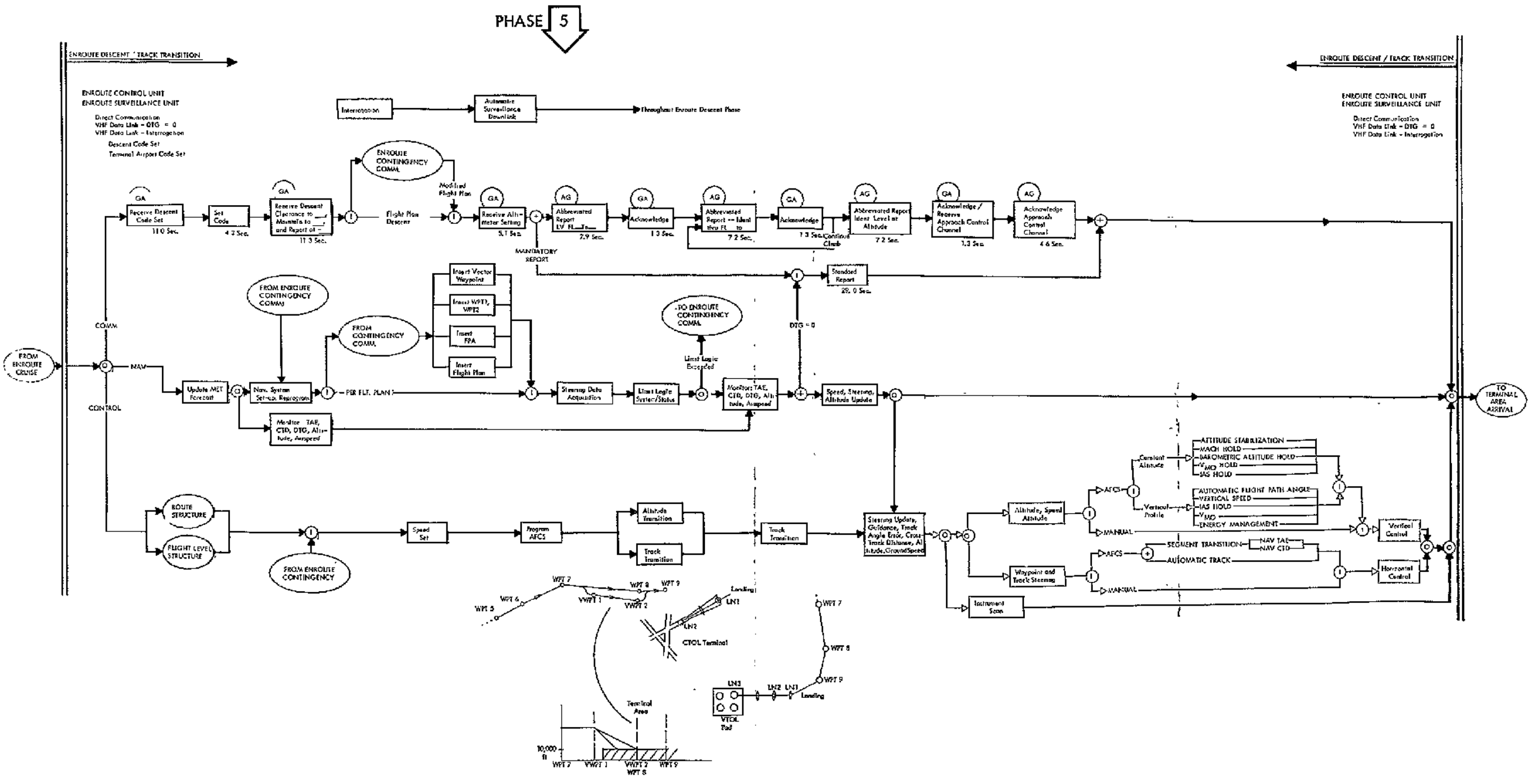
PRECEDING PAGE BLANK NOT FILMED.



1-31-A

Figure 14.

PRECEDING PAGE BLANK NOT FILMED



ENROUTE DESCENT TO TERMINAL AREA

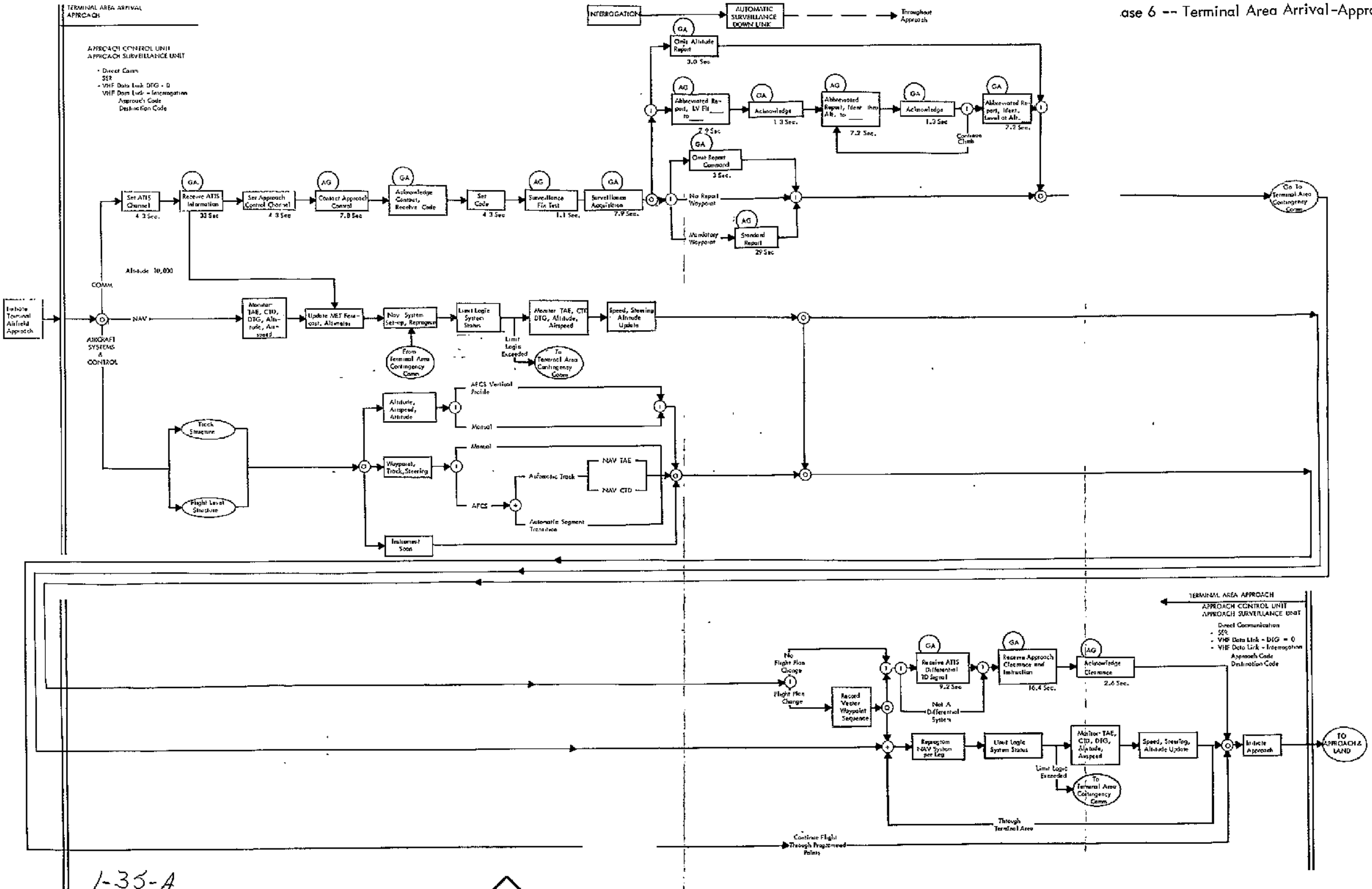
1-33-A

Figure 15.

FOLDOUT FRAME

FOLDOUT FRAME

PRECEDING PAGE BLANK NOT FILMED.



1-35-A

PHASE 6

Figure 16.

FOLDOUT FRAME

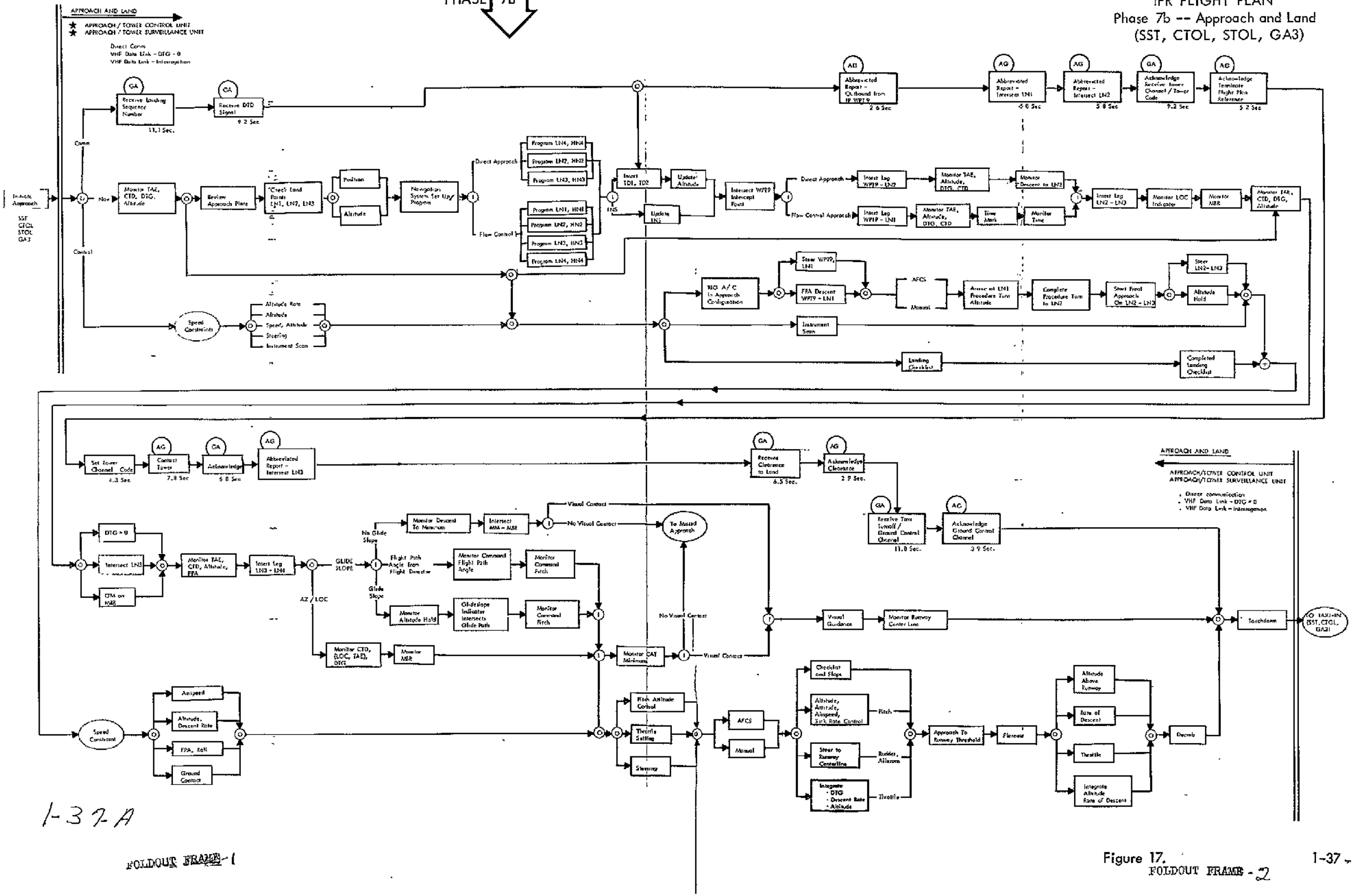
FOLDOUT FRAME

PRECEDING PAGE BLANK NOT FILMED.

EVENT SEQUENCE DIAGRAM

IFR FLIGHT PLAN
Phase 7b -- Approach and Land
(SST, CTOL, STOL, GA3)

PHASE 7b



1-37-A

Figure 17.

PRECEDING PAGE BLANK NOT FILMED.

EVENT SEQUENCE DIAGRAM

IFR FLIGHT PLAN

Phase 10 -- (Contingency Phase) -- Holding Pattern --

Phase 11 -- (Contingency Phase) -- Conting. Comm. --

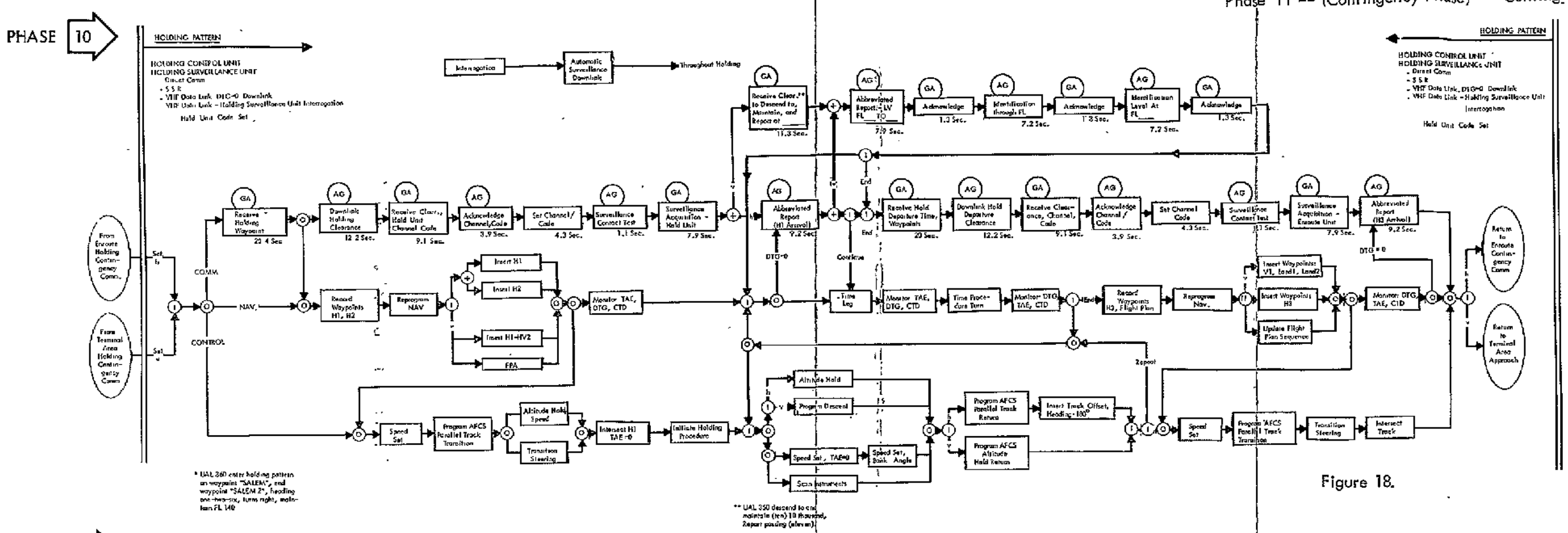


Figure 18.

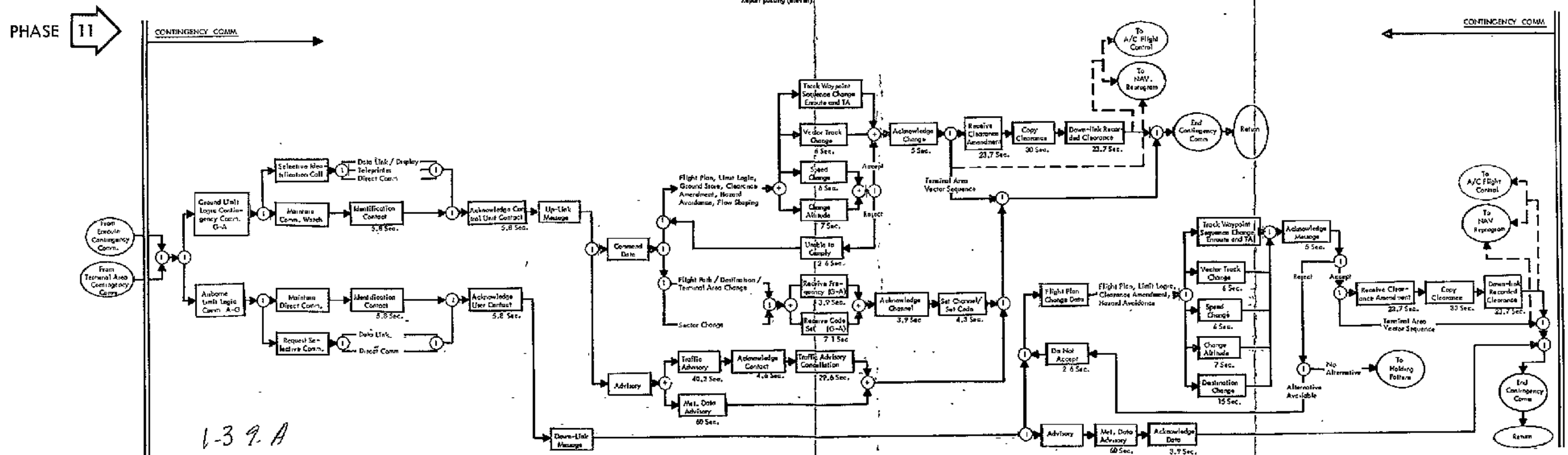


Figure 19.

1-39 A

1-39 - B

FOLDOUT FRAME - 1

FOLDOUT FRAME 2

2. REQUIRED FEATURES OF THE ATC SYSTEM

2.1 GENERAL

The functions of the existing ATC system which will be carried into any advanced configuration are those of surveillance, control and advisory service. Each of these functions has implications for design of the advanced airborne navigation and communication subsystems.

The principal requirement is to satisfy the ATC agency that any aircraft-supplied surveillance information meets the specified accuracy criteria, that the information will be available whenever required, that any inadvertent or planned alterations to flight path are immediately and automatically made known to the ground system, and that the required surveillance information cannot be compromised by a blunder committed in the cockpit without, at the same time, providing an alerting signal to the ground system.

Thus it is seen that a fundamental relationship must be preserved between aircraft and control agency . . . the flow of traffic is regulated at the discretion of the controller, subject to pilot acceptance of instructions. The pilot interfaces with the ATC system through his acceptance of a clearance and subsequent compliance with pertinent IFR or VFR procedures. He also accepts tactically motivated steering commands, commands to change communication channels, by modifying transponder identification codes as requested and through his acceptance of changes in clearance.

Aircraft position is generated today through use of ground based radar; pilot intentions are signified through use of pilot-initiated position reports and use of flight strips within the control agency. Advisory information is supplied to the aircraft as required or requested. These advisories may include information about traffic, weather, hazards to flight, and terninal area information of significance to the pilot.

The navigation/traffic control system general requirements are summarized in Table XVII.

TABLE XVII

ATC-RELATED NAVIGATION FUNCTIONS

Commonality and Ground Use of Data
Interface to ATC Surveillance Unit
Respond to Traffic Control Unit
Provide Holding Capacity
Provide Slant Tracks
Provide for Waypoint Vectoring
Automatic Reporting
Supplement Radar Surveillance Data per Flight Phase
Tactical Flight Control

2.2 SEPARATION CRITERIA

Requirements on the advanced navigation and traffic control system were generated from an evaluation of criteria set forth by the FAA in the context of the forecast traffic load. These requirements, expressed in terms of cross-track and along-track separation in nautical miles and altitude separation in feet, were translated into an accuracy specification by applying a 1/10 ratio rule rather than the more typical 1/3 or 1/7 (3σ, 7σ) rules. The results of this assessment are tabulated in Table XVIII.

TABLE XVIII
NAVIGATION SYSTEM REQUIREMENT - SEPARATION CRITERIA
(STANDARD AND SURVEILLANCE INFORMATION NEEDS)

Separation Factor		Approach						Enroute						Departures/Arrivals							Holding	Minimum Summary
		3 nmi., max AT radar sep.	2 nmi., min AT radar sep.	AILS CT at 15 nmi ± 0.6 nmi	ILS CT at 20 nmi ± 3.3 nmi	AILS Alt. at 15 nmi ± 400 ft.	ILS Alt. at 10 nmi ± 400 ft.	15 min. AT (high & Lo Alt.)	16 miles CT (high Alt)	60 miles CT (oceanic)	5 miles CT (lo Alt)	500 ft., below FL 290	1000 ft., above FL 290	5 min AT, when crossing altitude levels	5 min AT, lead aircraft ΔV > 20 knots	3 min AT, lead aircraft ΔV > 40 knots	3 min, Divergent heading	1 min, Divergent landing with positive CT Sep.	10nmi, altitude levels crossed	5 nmi, divergent tracks	From airways and other enroute traffic 5 nmi, 500 ft	* σ_{AT}, σ_{CT} σ_h
GA1 GA2	σ_{AT}	visual						3.8			0.5			1.2	1.2	0.8	0.8	0.3	1.0	0 5	0.5	0.3
	σ_{CT}													0.5	0.5	0.5	0.5	0.5	0.5	0.5	0 5	0.5
	σ_h											50	100	50							50	50
GA3 CTOL Jet VTOL STOL	σ_{AT}	0.3	0 2					7 5						2 5	1.2	1.5	1.5	0.5	1.0		0 5	0.2
	σ_{CT}			0 06	0 33				1.6		0 5			0 5	0.5	0.5	0 5	0 5	0 5	0 5	0.5	0.06
	σ_h					40	40					50	100	50							50	20
SST	σ_{AT}	0.3	0 2					30						2.5	1.2	1 5	1.5	0.5			0.5	0.2
	σ_{CT}			0.06	0 33				1.6	6.0	0.5			0 5	0.5	0 5	0.5	0.5			0.5	0.06
	σ_h					40	40					50	100	50							50	40

σ_{AT} in nmi, σ_{CT} in nmi, σ_h in ft.

* Note: See List of Symbols and Nomenclature for a listing and definition of these 3σ values.

2.3 FLIGHT PLAN CONTROL

A measure of system performance was devised for use in the advanced ATC system which relates aircraft progress with respect to an assigned flight profile to credibility of ETA, or ability to make good an assigned or required time of arrival (RTA). The traffic control system employs aircraft-generated surveillance information or estimated time of arrival (ETA) as a means to ascertain pilot intentions and controller-generated ETA to validate navigation information and as a means to forecast potential conflict with respect to a future waypoint or navigational fix. A measure of system performance can be generated through a comparison of airborne-derived surveillance data and ground-based computer-processed flight plan data.

Errors in the sensed or calculated variables used by the airborne system to compute ETA identify requirements on the system. By specifying the tolerance on ETA which will be accepted by the postulated ATC system, navigation system requirements can be derived. Table XIX summarizes the results of the evaluation performed in this study.

TABLE XIX
NAVIGATION SYSTEM REQUIREMENTS - FLIGHT PLAN CONTROL

USER	USER REQUIREMENT *				
	ΔETA minutes	σ_{CT} nmi	σ_{AT} nmi	σ_A deg.	σ_V percent
GA1, GA2	0.6	0.5	0.5	1.4	6.7
GA3, CTOL Jet VTOL, STOL, SST (Low altitude enroute) *	0.33	0.5	1.1	0.8	2.2
GA3, CTOL Jet, VTOL, STOL (High altitude enroute)	0.33	0.5	2.3	0.8	2.2
SST	0.33	1.6	4.4	0.15	0.8

*Also for terminal area with Alt. < 10,000 ft

2.4 RADAR SURVEILLANCE

Any candidate airborne navigation system which is intended to supply independent surveillance information for purposes of traffic control must be at least as accurate as is ground based radar. Table XX summarizes the performance capability of ground based systems.

TABLE XX
NAVIGATION REQUIREMENT - RADAR SURVEILLANCE

	Ground Unit Taxi In, Taxi Out, To Departure	Terminal Area Unit* Departure, Air Route (Lo), Appr, Stack Unit, Final Appr.			Air Route Unit* Air Route, Stack (continental)			Minimum Summary
		10 nmi	20 nmi	50 nmi	50 nmi	100 nmi	200 nmi	
GA1, GA2	NA	0.35	0.70	1.8	1.8	3.6	7.2	0.35
GA3, CTOL SST	0.43% @1.4 nmi = 36 ft	0.35	0.70	1.8	1.8	3.6	7.2	0.35
VTOL	0.43% 4 ft	0 35	0.70	1.8	1.8	3.6	7.2	0.35
STOL	0.43% 20 ft	0.35	0.70	1.8	1 8	3.6	7.2	0.35

*All units in nmi

These requirements will subsequently be combined with those generated in Section 1.1, Navigation Accuracy Requirements from Traffic Activity Forecasts, and with the area navigation, approach and landing requirements generated in Section 3.1. These are summarized in Table XXIV of Section 3.2.

2.5 COMMUNICATION SYSTEM REQUIREMENTS

A brief investigation was made of the communication system requirements based on the traffic forecast and estimated system information requirements. A VHF or UHF carrier was assumed as the transmission link.

The data and voice links between aircraft and ground-based systems must be capable of relaying all required messages whenever demanded by the ground system and/or according to a specified schedule.

Although it was beyond the scope of this study to determine communication system tradeoffs, several well-understood assumptions were employed. Binary coding was assumed, current VHF modulation techniques and signal power were considered adequate for use in the domestic airspace, frequency response of VHF modulation at 10 kHz was assumed to provide an adequate bandwidth.

The analysis undertaken in the study is described in Appendix C, Volume III. Data requirements and system capacity of both airborne and ground-based systems are summarized in Tables XXI and XXII respectively.

TABLE XXI
COMMUNICATION SYSTEM, STANDARD REPORT DATA REQUIREMENTS

	Option	Data Words	Bits	Capacity Bits/Sec Approach	Departure	Enroute-Low	Enroute-High
SST	1 2	11 11	165 155	10^3-10^4	10^3-10^4	10^3	10^3
GA3-CTOL-VTOL-STOL	1 2	11 11	162 152	10^3-10^4	10^3-10^4	10^3	10^3
GA1-GA2	1 2	11 11	145 122	4×10^3-10^5	4×10^3-10^5	4×10^3-10^5	-

TABLE XXII
COMMUNICATION SYSTEM, GROUND STORAGE REQUIREMENTS

Floating Point Ground Store	Air Carrier/GA3 Low	Air Carrier/GA3 High	GA1 - GA2 Low	GA1 - GA2 High
16 Bit Data Words	550	4,100	6,720	48,100
Total K Bits	91	675	970	7,000

3. REQUIRED FEATURES OF THE AREA NAVIGATION, APPROACH AND LANDING SYSTEMS

3.1 APPROACH AND LAND CRITERIA

Requirements on the navigation system can be generated from an evaluation of approach and landing accuracy criteria. As a minimum, the navigation system must provide sufficient accuracy in knowledge of position and speed to permit the aircraft to capture the localizer and glide-slope, or their equivalent, of the runway in use. The envelope of suitable trajectories then defines the bounds of acceptable cross-track, along-track, altitude and rate errors.

These requirements on the airborne system become significantly tighter if it must meet landing system performance criteria as well. Table XXIII summarizes the 3σ requirements on the system . . . the upper two rows describe the Approach case, the lower three rows the All Weather Landing case.

TABLE XXIII
NAVIGATION REQUIREMENT - APPROACH AND LAND (All Weather)

		Landing						Taxi	Approach	
		Cat I	Cat II		Cat III				ILS σ_A	AILS σ_A
			a	b	a	b	c			
GA1, GA2 (not used in less than 5 n mi RVR (IMC)		NA	NA	NA		NA		NA		
GA3	*σ_{AT}	260	160	120				35		
	*σ_{CT}	75	75	75		NA		35		
	*σ_h	20	20	10				-		
	σ_A	1°	1°	1°				1°		
CTOL Jet**	σ_{AT}	260	160	120	70	15	0			
	σ_{CT}	75	75	75	75	75	75		0.1°	0.03°
	σ_h	20	20	10	0	0	0			
	σ_A	1°	1°	1°		1°				
VTOL	σ_{AT}							15		
	σ_{CT}	25	25	25	25	25	25	15		
	σ_h							-		0.03°
	σ_A							1°		
STOL	σ_{AT}							25		
	σ_{CT}	50	50	50	50	50	50	25		
	σ_h							-		
	σ_A							1°	0.1°	0 03°
CTOL Jet & SST	σ_{AT}							35		
	σ_{CT}	75	75	75	75	75	75	35	0.1°	0.03°
	σ_h							-		
	σ_A							1°		

*All units in ft.

**σ_{AT}, σ_A, σ_h hold for VTOL, STOL, CTOL Jet & SST

3.2 AREA NAVIGATION CRITERIA

The activities completed in Sections 1 and 2 lead to the definition of a set of navigation accuracy requirements. Six related sources of these requirements have been combined using vector analysis: (1) the 1975 – 1985 Traffic Activity Forecasts, (2) separation standards, (3) flight plan control limits, (4) all-weather and radar surveillance criteria, (5) approach criteria and (6) landing criteria. The navigation accuracy constraint was defined as a vector consisting of the 3σ values of components: along/cross track error, altitude error, and heading error. Table XXIV presents a summary of the minimum 1975-1985 Horizontal Accuracy Requirements for the six classes of User aircraft. It will be noted that the requirement varies with flight phase. All air carrier user classes were determined to require a horizontal navigation capability of 0.5 nmi (3σ throughout terminal area flight, while the requirement for general aviation was determined to be 0.3 nmi for GA1 and GA2, and 0.5 nmi for GA3.

3.3 QUALITATIVE SUMMARY OF AREA NAVIGATION REQUIREMENTS

(1) Permit off-airways operation

(2) Provide path stretching and speed scheduling capability.

(3) Provide flexibility in selection of departure and approach paths through use of parallel and slant tracks.

(4) Desired system characteristics: independent of number of users, local topography, multi-path effects, or atmospheric anomalies; frequency protected; LOS independent; time independent; real time solution; and map referenced.

TABLE XXIV
SUMMARY - MINIMUM HORIZONTAL ACCURACY REQUIREMENT
IN CONTROLLED AIRSPACE (1975-1985)

FLIGHT PHASE \ AIRCRAFT	IFR AND VFR					VFR FLIGHT PLAN REFERENCE	
	SST	CTOL JET	VTOL	STOL	GA3	GA2	GA1
TAXI	35 ft	35 ft	15 ft	25 ft	35 ft	NA	NA
TAKE-OFF	35 ft	35 ft	15 ft	25 ft	35 ft	NA	NA
CLIMB-OUT	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.3 nmi	0.3 nmi
ENROUTE - LOW	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi
ENROUTE - HIGH	1.6 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	NA	NA
ARRIVAL	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi
DESCENT	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.5 nmi	0.3 nmi	0.3 nmi
APPROACH	360 ft	360 ft	360 ft	360 ft	360 ft	0.3 nmi	0.3 nmi
LAND - CAT II	75 ft	75 ft	25 ft	50 ft	75 ft	NA	NA
LAND - CAT IIIC	15 ft	15 ft	15 ft	15 ft	15 ft	NA	NA
TAXI	35 ft	35 ft	15 ft	25 ft	35 ft	NA	NA
HOLDING	0.12 nmi	0.12 nmi	0.12 nmi	0.12 nmi	0.12 nmi	0.12 nmi	0.12 nmi

4. EVALUATION OF CANDIDATE NAVIGATION AIDS

The contractor was asked to evaluate four condidate area navigation aids as to their capability to supply position information to the seven categories of Users operating in the 1975 - 1985 domestic air space.

4.1 DECCA, LORAN C AND NAVSAT

The four candidates, Decca, Loran C, NAV/SAT and hybrid radio-inertial, were evaluated with respect to both the qualitative and quantitative criteria set out in Section 3.

4.2 OTHER CANDIDATE SYSTEMS

To provide a basis of comparison,as well as to make the evaluation more complete, VOR/DME and Omega were also considered. All of the Time Difference systems were assumed to be capable of accepting a calibration signal, called differential time differencing, as a means to minimize the effects of certain propogation anomalies. Preliminary analysis indicates that the result of performing the calibration would be an increase in accuracy sufficient to meet the 3σ horizontal accuracies required for approach. The VOR/DME system was also evaluated in a PVOR/PDME configuration.

One of the major objectives of the NAVTRACS program was to recommend areas for automation which could significantly reduce cockpit workload and possiblity of human error. Prior to the workload/automation tradeoff analysis,the performance capabilities of the candidate navigation systems were carefully evaluated. Appendix F, Volume III, presents a complete review of the candidate systems.

To summarize, eight basic navigation systems were considered. The initial list of candidates included rho-theta, NAVSAT, and ground-based time difference (GBTD) systems. The rho-theta systems were:

- rho-theta (VPR/DME)
- rho-theta with course line computer
- precision rho-theta (PVOR/PDME)
- precision rho-theta with course line computer

The time difference systems considered were:

- NAVSAT
- VLF-CW (Omega)
- LF-Pulsed (Loran C)
- LF-CW (Decca)

4.3 THE OPERATIONAL REQUIREMENT

Table XXV summarizes the capability of each of the system configurations to satisfy the operational requirement. In the tabulation:

- \+ meets requirement
- o marginally meets requirement
- \- does not meet the requirement

Three systems - NAVSAT, LF/CW GBTD and LF-Pulsed GBTD - were found to completely satisfy the performance requirements.

TABLE XXV
NAVIGATION REQUIREMENTS CHECKLIST
NAV SAT, RHO-THETA, AND GBTD

NAV SYSTEM REQUIREMENT \ NAV SYSTEM	VOR/ DME	PVOR/ PDME	VOR/ DME CLC	PVOR/ PDME CLC	NAV SAT	DIFF NAV SAT	VLF/CW	LF/CW	LF/PULSED
NON-SATURABLE	-	-	+	+	o	o	+	+	+
MINIMIZE NAV FREQUENCY	-	-	-	-	+	+	+	+	+
LOS INDEPENDENT	-	-	-	-	+	+	+	+	+
AREA COVERAGE	-	-	o	o	+	+	+	+	+
REAL TIME	+	+	+	+	o	o	+	+	+
ALL WEATHER	+	+	+	+	+	+	o	+	+
MINIMAL NUMBER GROUND STATIONS	-	-	-	-	+	+	+	o	o
TIME INDEPENDENT	+	+	+	+	+	+	o	o	+
FLEXIBLE TO ATC ROUTE STRUCTURE/VECTOR	+	+	+	+	+	+	+	+	+
MAP REFERENCE	+	+	+	+	+	+	+	+	+
COMMON OUTPUT FORMAT	+	+	+	+	+	+	+	+	+
GROWTH ORIENTED	-	-	o	o	+	+	o	+	+
ADAPTIVE FLIGHT PATH CAPABILITY*	-	-	o	o	+	+	+	+	+
GENERATE ATC SURVEILLANCE DATA*	o	o	o	o	+	+	+	+	+
COMPATIBLE WITH INFO NEEDS*	+	+	+	+	+	+	+	+	+
SATISFY ACCURACY CONSTRAINT	-	+	-	+	+	+	o	+	+

*Dependent upon onboard computer
**Dependent on data link message content

4.4 ACCURACY REQUIREMENTS AND CAPABILITIES

Figure 20 summarizes the accuracy that is attainable with the candidate navigational aids. The details of the supporting analysis are presented in Appendix F (Candidate Nav Systems) of Volume III - Appendices. The accuracy is expressed as the 3σ horizontal component. The spread on the system errors is caused by varying mission geometry, propagation conditions, conductivity conditions, or equipment specification. A 0.5 nmi (3σ) navigation accuracy requirement exists for all user aircraft operating in enroute congested airspace and terminal areas. It can be attained utilizing rho-theta, NAVSAT, and GBTD systems. The 0.3 nmi (3σ) climb, descent, and approach navigation requirement is set for general aviation users and can be achieved using precision rho-theta, NAVSAT, and GBTD. The required area navigation accuracy for establishing a holding pattern is 0.12 nmi (3σ). Precision approach accuracy for the air carrier user is 360 ft. Although precision rho-theta and GBTD systems can marginally meet the holding pattern requirements, the precision approach requirement can only be met with the NAVSAT system. GBTD cannot meet the requirement. However, preliminary analysis indicates that the GBTD system can be modified to reduce the system errors to an acceptable level. Differential NAVSAT and differential GBTD, when integrated with an accurate velocity source,can also meet the CAT-(IIa) landing requirement.

Based on the (1975-1985) operational requirement, GBTD (LF-CW, LF-Pulsed), precision rho-theta, and NAVSAT systems are acceptable navigation aids for enroute and terminal area flight. As approach aids, NAVSAT, differential NAVSAT, differential LF/CW and differential LF/pulsed systems are candidates. Because it is at least marginally acceptable,a rho-theta system was also evaluated as a part of the pilot workload analysis.

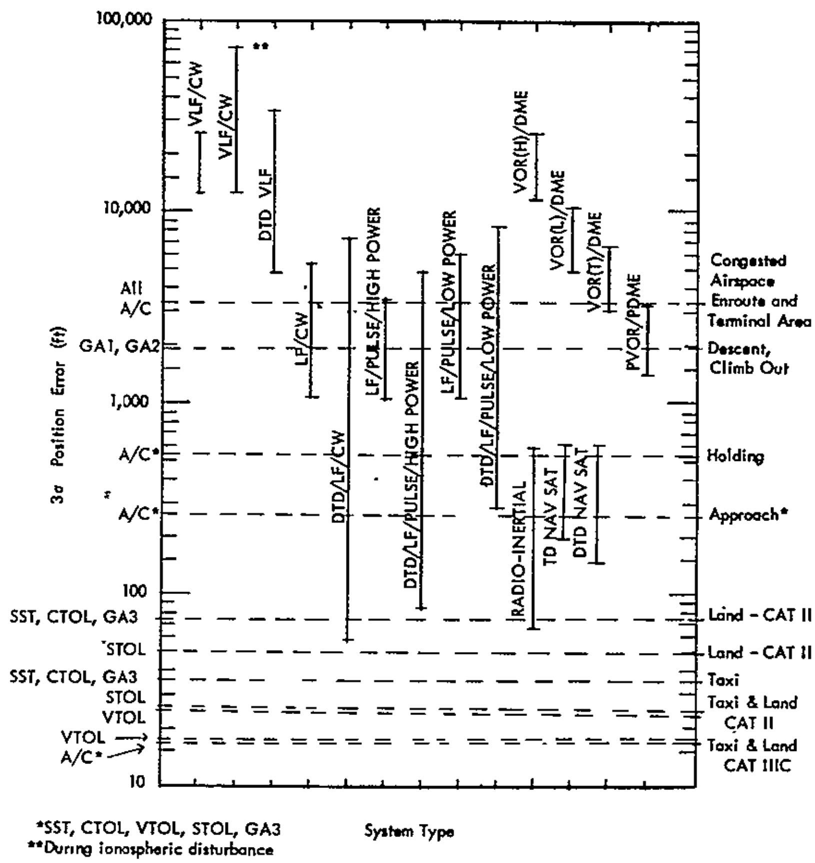


Figure 20. Summary of Navigation System Requirements - 1975-1985

5. CONFIGURE A CANDIDATE ATC SYSTEM

A model of an advanced navigation and air traffic control system was developed as a means to evaluate automation benefits and new technology requirements. The system was configured in anticipation of full acceptance of area navigation, data link,and reduced dependency on manual radar-controller surveillance procedures by the 1980's.

The system developed in this study is completely responsive to traffic activity forecasts, pilot workload criteria, ATC requirements and area navigation criteria set out in earlier sections of this volume.

5.1 SYSTEM CONCEPT

The advanced ATC system incorporates,as automated system features, those functions which are closely allied to present cockpit duties. It embodies a Flight Plan Reference concept, a retrievable flight plan, a Limit Logic concept, an area navigation aid, a data link and a capability for development of required surveillance data within the airborne system.

5.2 FLIGHT PLAN REFERENCE

A mandatory feature of the advanced traffic control system requires that all Users of controlled airspace file flight plans,whether operating VFR or IFR. The result of using this procedure is that the ATC agency is fully advised of both the presence of all aircraft in the controlled airspace and the intentions of all pilots. This allows the ATC to make continuous evaluation of the situation, increase the use of strategic procedure, and anticipate the need for tactical actions under conditions of reduced stress.

The concept also imposes a discipline on the pilot in the form of a requirement to go where he has stated an intention to go. Finally it provides the basis for the implementation of a Limit Logic capability.

5.3 RETRIEVABLE FLIGHT PLAN

The airborne system is designed to maintain continuous operational cognizance of the flight plan while the ground based traffic unit concurrently maintains a data file on each flight. Either unit may call the flight plan for review or modification at will.

5.4 LIMIT LOGIC

The limit logic is comprised of variables which describe aircraft progress with respect to an approved flight plan. When these variables are exceeded, the pilot is alerted,and concurrently contact with the ground is initiated via data link. The variables are increments in ETA, error in altitude, deviations in assigned speed or cross track distance and/or fuel remaining. This capability is intended to restrict the volume of required cross-talk between ground system and airborne system to those occasions when a deviation is observed or when the ground system requires an update.

5.5 OPERATIONAL CONSIDERATIONS

The system was designed to allow ATC to institute flow control or to modify the clearance in other ways through automatic insertion into the airborne system of arbitrary turning points designed to extend the path length or to keep the aircraft within a more favorable altitude block in order to relieve congestion in the terminal area. In this study, these points are called Vector Way Points (VWP) to distinguish them from the flight plan way points.

As long as the aircraft maintains assigned track and speed, that is, arrives on time over required checkpoints, no communication with the ground is required. When the aircraft passes over a mandatory reporting point the system automatically outputs aircraft ident, waypoint designator and time.

Complete capability is maintained on the part of either controller or ground based traffic unit to detect any alterations in routing, altitude, speed, or combination thereof initiated by the aircraft.

5.5.1 Cockpit Oriented ATC Features

- Flight Plan Reference - Aircarrier and general aviation users file flight plans. These are filed on both IFR and VFR flights. Controlled VFR operations occur only in controlled, congested airspace. VFR flights in uncongested regions need not comply.

- Retrievable Flight Plan - The airborne system maintains cognizance of a stored flight plan. Simultaneously, ATC automatically monitors the progress of each flight with respect to the flight plan and the traffic flow. This curtails the total volume of communications.

- Limit Logic Concept - This concept implements the Flight Plan Reference. The Limit Logic variables are increments in estimated time of arrival, assigned altitude, forecasted speed, crosstrack distance, and fuel remaining. Exceeding these limits alerts the pilot and the A-G-A communications.

- Area Navigation, Airborne Computer, and Data Link - Area navigation permits parallel track, slant track, speed control, and volume navigation operations. These subsystems perform the three functions of flight plan storage, Limit Logic Computations, and navigation and guidance computations. The VHF data link supplies the ATC surveillance information.

- Automated Ground System - This system is postulated to make effective use of the unambiguous navigation surveillance information, to advance and stress the role of the controller as a decision maker.

6. EVALUATION OF WORKLOAD AND SYSTEM AUTOMATION BENEFITS

The pilot workload analysis reported on in this section was the focal point of the NAVTRACS study. To assess performance of the advanced navigation/air traffic control system, the study requirement infers that the postulated system should at least not increase the workload of the pilot, as a minimum goal. Clearly any proposed system must be capable of accommodating all user vehicles which are forecast to be operational during the period of interest. Any areas of activity which appeared to cause an unreasonable increase in workload became candidates for automation.

The workload analysis required development of assumptions about almost every element of the future system: premises were required regarding organization of the future ATC system, acceptable procedures, performance of the vehicles, and availability of avionics equipment. Data was taken from NASA, USAF and FAA supported studies. Equipment features were postulated from ARINC specifications, from documents supplied by avionics manufacturers, and from discussions undertaken with professional pilots, navigators, and general aviation pilots. Where present equipment did not provide for necessary control-display operations (of future equipment), "straw man" panels and operational procedures were created.

Figure 21 illustrates the methodology* utilized in the workload analysis.

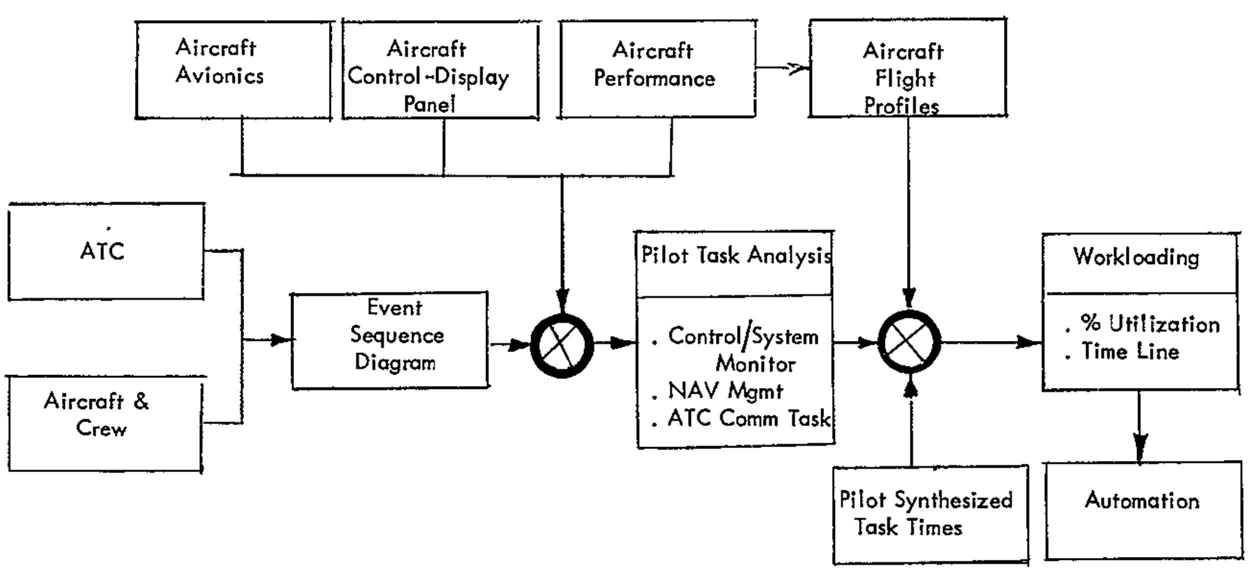


Figure 21. Pilot Workloading Analysis Methodology

* Note: Figure 10, Page 1-24, is repeated above for easy reference.

6.1 DEVELOPMENT OF WORKLOAD MEASUREMENT CRITERIA

To understand the need for automation of navigation and communication functions and equipment operation, it was necessary to develop an appreciation of the tasks performed today by aircrew personnel in managing their aircraft.

The workload methodology was based on four sources of information: synthesized task times experimentally determined in pilot studies which specify pilot task time in performing mechanical functions; results of a series of field trips in which aircrew personnel were carefully questioned about the manner in which they performed their jobs; the refinement of certain workload and pilot utilization estimators developed by personnel of this organization; and data obtained from a series of simple, timed, paper and pencil tests utilizing a paper cockpit mockup. The subjects were licensed aircrew personnel, each of whom had significant experience with the tasks under investigation.

Two present-day aircraft, a four-engine CTOL jet transport and a single-engine GA2 aircraft, provided the baseline information. The pilot tasks in the CTOL jet were assumed to be sufficiently like those of the sophisticated GA3 aircraft that an assessment of GA3 was not made. Task times for GA2 aircraft were assumed to be sufficiently like those of GA1 that a separate workload assessment was felt not to be necessary.

Operator tasks and task times for the VTOL and STOL aircraft were developed from a review of NASA documents and similar literature. Workload for the SST aircraft was developed from an extrapolation of operational experience of PNSI personnel, review of ARINC documents and airframe manufacturers' documents, and the results of an on-going PNSI study of Concorde performance utilizing an IBM 360-44 computer. In summary, pilot monitor and control workload estimates were prepared for four aircraft types (Tables D-VII, D-VIII, D-IX, and D-X); task times were estimated for the communications task (Tables D-V and D-VI); and for twenty navigation-related tasks (Table D-III) . . . . .all tables will be found in Volume III of this report.

The pilot workload analysis required a model of the human operator. Pilot performance was evaluated for the aircraft control and monitor, navigation management,and pilot/ATC communications tasks utilizing the rationale set out below. Experienced aircrew personnel were utilized as subjects. The model incorporated an operator transfer function devised to describe a motivated, well-trained operator performing relatively simple tasks such as closed-loop tracking utilizing compensatory displays; recognition of the effect of human response time on a desired or required action; execution time (as set out in standard texts); and synthesized task times.

The operator workload model was completed with two figures of merit, both quantified: task time and operator % utilization. Workloading was first assessed for operator-defined task times. Subsequently, a figure of merit was devised based on % utilization of the operator's faculties. This figure of merit was computed from the equation:

$$(1) \quad \% \text{ Utilization} = \frac{\text{Task Utilization}}{\text{Total Utilization}} \times 100$$

TABLE XXVI
NAVIGATION MANAGEMENT TASKS SUMMARY

Minimum Automation Navigation Management Event	Task Time, sec.		% Utilization	
	Ave.	Min.	Pilot	Navigator
In Flight Weather Evaluation	794	395	26.6	37.33
Inertial Navigation System Management	597	238	32.6	45.71
Doppler/Computer System Management	819	492	27.4	38.4
Loran A Manipulation	220	94	35.8	50.1
Loran C	265	255	26.3	36.8
Automatic Direction Finder	234	134	28.6	40.0
Fixing Radar	416	244	31.7	44.4
Weather Avoidance Radar	179	86	27.4	38.3
VOR/DME	245	139	26.5	37.1
CLC Management	194	117	23.9	33.5
Determination of Magnetic Course	146	72	33.4	47.5
Altitude Change Enroute	168	99	26.1	36.6
Monitoring Flight Plan Enroute (Fuel Management)	455	170	39.3	55.0
Copying and Acknowledging ATC Clearances (Oceanic)	124	59	28.6	40.0
Turbulence Penetration	17	9	19.4	27.9
Reroute by ATC During Enroute Phase	353	200	31.6	44.2
Radar Identification in Transition Zone	92	74	28.6	40.0
Altitude Change in Transition Zone	55	34	26.8	37.5
Navigation Management in Transition Zone	745	466	34.4	48.2
*Navigation Management of MMD	73	73	28.6	40.0

*No track monitor function

where Task Utilization = weighting factor per task
Total Utilization = weighting factor for % utilization of the operator's TOTAL faculties

To compute average % utilization for a series of tasks, the operator utilization must be averaged over the complete task interval. Thus:

$$\text{(2) Average \% Utilization} = \frac{1}{T} \int_{0}^{T} U\,dt$$

where T = the total period
U = task utilization factor in terms of percentage.

All task times and workload assessment reported in this study were based on carefully evaluated opinion of experienced aircrew members. Utilization of the private pilot in the performance of comparable tasks was increased by a factor of one-third to one-half, depending upon an assumption regarding experience and proficiency of the pilot. The effect on task times of inflight emergencies was not considered. The results of the methodology are summarized in Tables XXVI and XXVII. Table XXVI describes task time and related operator % utilization associated with twenty navigation-related tasks. Table XXVII, one of a set appearing in Appendix D, presents a listing of the individual sub-tasks making up the navigation event summarized in Table XXVI. Five tasks are described: inflight weather evaluation, INS management, Doppler/computer system management, Loran A manipulation, and Loran C (completed in Appendix D).

The careful quantification of each of the subtasks was later fitted to the aircraft mission profiles and tied to the Event Sequence Diagram for each user aircraft, and the resulting information used to build a picture of total pilot workload.

The communication workload was developed in a similar way. Tables XXVIII and XIX present a complete breakdown of typical VFR and IFR communications events and workload as a function of flight phase. Note that only 45 of the 118 individual transmissions experienced in the IFR case are listed for illustrative purposes. . . . .the complete set will be found in Appendix D.

In summary, the workload methodology, applied to the navigation management tasks, permitted assessment of the utilization of the operator's manual, visual and aural faculties. It explicitly evaluated the percent utilization of the operator in the performance of these tasks. Implicitly considered in evaluation of task times were such factors as: operator proficiency, stress level, fatigue, task criticality, and task difficulty.

The tasks and related workload measurements were critiqued in depth by general aviation, military, and air carrier pilots and navigators. The synthesized task times were generated for particular man/machine functions during particular portions of the aircraft flight phase. The evaluation assumed a trained, motivated, alert operator to be performing the tasks.

TABLE XXVII
NAVIGATION MANAGEMENT TASKS - (DETAILED) - (PARTIAL)

Event	Task	Time	Utilization Factor
In Flight Weather Evaluation	Check Time	1.2	3
	Check a/c position	1.8	3
	Make in flight weather observation	10	3
	Record	15-30	8
	Make in flight weather measurements (temp, w/v)	1.8-60	3
	Record	5-10	8
	Report	25-60	2
	Get forecast (either previously obtained or by radio)	30-300	8
	Modify forecast	60-120	11
	Modify ground speed if necessary	15	11
	Modify eta as necessary	60	11
	Modify fuel calculators	60-120	11
	Recalculate drift (general aviation)	45	11
	Recalculate hdg (general aviation)	5-60	11
	Copy forecasts	60-300	8
	Ave	794 sec	
	Max	1030	
	Min	395	
	Pilot/Copilot		26.6%
	Navigator		37 3%

Event	Task	Time	Utilization Factor
Inertial Navigation System Management	Switch on to stand by	1.1	8
	Align mode, gyro compass, nav mode	2 2	8
	Program way point(s)	42 ea	8
	Plot DR position	20	11
	Determine external fix	8-180	11*
	Plot fix LOP's ie VOR/DME, loran. Record and check time	3.2	11
	Determine DR position error North/South and East/West	20-30	8
	Determine along track error	20-30	11
	Determine across track error	20-30	11
	Determine track angle error	15	11
	Update present position by inserting correct co-ordinates while on memory	43 3	8
	Correlate magnetic heading with platform true heading	10-30	3
	Check eta way point	30-90	11
	Record	3-5	8
	Ave	430 sec	
	Max	522	
	Min	238	
	Pilot/Copilot		32 6%
	Navigator		45.71%

*Present position plus eight waypoints may be programmed in ARINC 561 INS

Event	Task	Time	Utilization Factor
Doppler/Computer System Management	Switch on	2.2	8
	Test	240	7
	Slew ground speed and drift	4	7
	Set required course	10-30	8
	Set required distance	10-30	8
	Determine system tracking error (STE)	15	11
	Offset computer for STE	4.3	8
	Check hdg	1.2	3
	Check drift	1.2	3
	Check track angle settings	1 8	3

Event	Task	Time	Utilization Factor
Doppler/Computer System Management (Cont'd)	Check distance settings	1.8	3
	Determine fix (Rho-theta, hyperbolic)	8-180	8-11
	Plot DR position	20	11
	Plot fix	60-240	11
	Revise STE (across track error)	30-60	11
	Determine along track error	10-30	11
	Calculate course change	10-45	11
	Initiate course change	4 3	8
	Correlate hdg., drift, and track in auto coupled mode	7.4-10	3
	Reset distance along track	4 3	8 Update
	Reset cross track indication	4 3	8
	Reset required track, trouble shoot	4 3	8
	Recycle breakers	4 2 ea	8
	Switch off and on	1 1	8
	Check eta way point	30-90	8
	Record	3-5	8
	Ave	819 sec	
	Max	1034	
	Min	492	
	Pilot/Copilot		27 4%
	Navigator		38 4%

Event	Task	Time	Utilization Factor
Loran A Manipulation	Switch on	1.1	7
	Estimate DR position for fix	10-30	11
	Predict relative signal strength and sky ground wave mix for one chain	10-60	11
	Match pulses	30-180	11
	Read time difference and record	4 2-10	8
	Determine and apply sky wave corr	20	11
	Read and record time and doppler distance	8 4-15	11 DR pos.
	Add cross track if applicable	10	11
	Plot LOP	10-30	11
	Ave	220sec	
	Max	346	
	Min	93.7	
	Pilot/Copilot.		35 8%
	Navigator		50 1%

Event	Task	Time	Utilization Factor
Loran C	Switch power - ON	1 1	7
	Estimate DR position for a fix	10-30	11
	Warm up	300	0
	*Select chain	2 1	8
	*Select Loran C	2 1	7
	*Set bandwidth control - narrow	2 1	7
	*Set function switch - M	2 1	7
	*Set readout switch - A/B	2 1	7
	*Select timebase - 1	2.1	7
	Slew master pulse groups to left of scope	10	8
	Set bandwidth control - wide	2 1	7
	Select timebase - 2	2 1	7
	Align master pulse with gates	20	8
	Select timebase - 3	2 1	7
	Align gate with third cycle of first pulse	20	8
	Set function switch - A	2 1	7

TABLE XXVIII
TYPICAL VFR COMMUNICATIONS (A-G AND G-A)

TYPICAL VFR A-G AND G-A COMMUNICATIONS

Flight Phase	Message No	Type of Comm	Actual Communication	System with Selective Call #Words	Time Sec	Present System #Words	Time Sec
TAXI IN AND OUT	1	G/A	ATIS	50	33 6	50	33 6
	2	A/G	Cleveland Ground Control this is Cessna November 6032 Bravo	0	0	11	7 8
	3	G/A	November 6032 Bravo Cleveland Ground	0	0	8	5 8
	4	A/G	Cessna 6032 Bravo VFR Detroit Wayne	3	2 5	9	6 5
	5	G, A	November 6032 Bravo cleared to runway 21 left via taxi-ways Alpha and Bravo Contact tower one-one-niner-point-three when ready	20	13 8	26	17 7
	6	A/G	One-one-niner-point-three	5	3 9	5	3 9
	7	A/G	Detroit Ground this is Cessna 6032 Bravo Would like to go to General Aviation Terminal via taxiways Alpha and Charlie Hold short taxiway Charlie for Beaumont 451	22	15 1	32	21 7
	8	G/A	Roger	1	1,2	1	1 2
DEPARTURE	9	A/G	Cleveland Tower this is Cessna 6032 Bravo VFR Detroit ready to go	5	3 9	15	10 5
	10	G/A	November 6032 Bravo cleared for immediate takeoff Maintain runway heading Contact departure control one-two-three-point-seven	15	10 5	21	14,4
	11	A/G	One-two-three-point-seven	5	3 9	5	3,9
	12	A/G	Cleveland Departure Control this is Cessna 6032 Bravo just off Runway two-one, No transponder	7	5 2	18	12 4
	13	G/A	November 6032 Bravo climb to and maintain three thousand, Turn right heading two-seven-zero Radar contact	14	9 8	20	13 8
	14	A/G	Cessna 6032 Bravo level at three thousand	4	3 2	10	7,2
	15	G/A	Roger	1	1 2	1	1 2
	16	G/A	November 6032 Bravo 20 miles west of field - Radar services terminated, Frequency change approved Resume normal navigation	14	9 8	20	13 8
	17	A/G	Roger,	1	1 2	1	1 2
	18-21	G/A	November 6032 Bravo traffic Eleven o'clock West bound 3 miles, Slow moving	36	24 3	69	40 2
	22-25	A/G	Negative contact,	6	4 5	6	4 5
	26-29	G/A	November 6032 Bravo traffic no longer a factor	20	13 8	44	29,6

TABLE V (cont'd)

Flight Phase	Message No	Type of Comm	Actual Communication	System with Selective Call #Words	Time Sec	Present System #Words	Time Sec
ENROUTE	30	A G	Cleveland Center this is Cessna 6032 Bravo one-two-six-point-three	0	0	15	10 5
	31	G A	November 6032 Bravo Cleveland Center	0	0	8	5 8
	32	A/G	Cessna 6032 Bravo VFR Detroit Wayne level at six thousand five hundred twenty miles west of Cleveland Hopkins Heading two-seven-zero Request traffic advisories	22	15 1	28	19 0
	33	G/A	November 6032 Bravo turn left heading heading one-eight-zero for radar identification.	10	7 2	16	11 1
	34	A/G	One-eight-zero	3	2 5	3	2,5
	35	G/A	November 6032 Bravo Radar contact	2	1,9	8	5 8
	36	G A	November 6032 Bravo twenty miles southeast of Detroit Wayne contact approach control one-two-three-point-seven.	14	9,8	20	13 8
	37	A G	One-two-three-point-seven.	5	3 9	5	3 9
	38-40	G/A	November 6032 Bravo traffic Eleven o'clock Westbound three miles slow moving.	27	18,4	45	30 3
	41-43	A/G	Negative contact	6	4,5	6	4 5
	44-46	G/A	November 6032 Bravo traffic no longer a factor.	15	10 5	33	22,3
ARRIVAL	47		ATIS	50	33 6	50	33 6
	48	A G	Detroit Approach Control this is Cessna 6032 Bravo	0	0	11	7 8
	49	G/A	November 6032 Bravo Detroit approach control	0	0	9	6 5
	50	A G	Cessna 6032 Bravo twenty miles Southeast of field heading three-three-zero degrees level at six-thousand-five hundred Landing	16	11 1	22	15 1
	51	G/A	November 6032 Bravo turn right heading zero-six-zero degrees for identification	9	6 5	15	10,5
ARRIVAL	52	A/G	Zero-six-zero	3	2 5	3	2 5
	53	G, A	November 6032 Bravo Radar contact Resume navigation.	4	3 2	10	7,2
	54	G/A	November 6032 Bravo five miles Southeast of field Contact tower one-one-niner-point-one	12	8 5	18	12 4
	55	A/G	One-one-niner-point-one	5	3 9	5	3 9
	56-59	G/A	November 6032 Bravo traffic eleven o'clock Westbound three miles slow moving	36	24 3	60	40 2
	60-63	A/G	Negative contact	8	5 8	8	5 8
	64-67	G/A	November 6032 Bravo traffic no longer a factor	20	13 8	44	29 6

TABLE XXIX
TYPICAL IFR COMMUNICATIONS (A-G AND G-A)

Flight Phase	Message No	Type of Comm.	TABLE VI (cont'd) Actual Communication	System with Selective Call: Words	System with Selective Call: Time Sec	Present System: Words	Present System: Time Sec
ENROUTE	46	A/G	New York Center this is Cessna 6032 Bravo one-one-niner-point-zero	0	0	16	11 2
	47	G/A	November 6032 Bravo this is New York Center Change to code one-zero-niner-zero Squack ident Radar contact.	11	7 9	22	15 1
ENROUTE (cont)	48	G/A	November 6032 Bravo contact New* York center one-two-three-point-five-five	10	7,2	16	11,2
	49	A/G	One-two-three-point-five-five	6	4 6	6	4 6
	50	A/G	New York center this is Cessna 6032 Bravo level at Flight-level one-eight-zero over Salem at fifteen estimate Bridgewater twenty-two Litchfield next.	18	12 5	29	19 7
	51	G/A	Roger 6032 Bravo	1	1 3	6	4 6
	52	A/G	New York center this is Cessna 6032 Bravo one-two-three-point-five-five.	0	0	16	11 2
	53	G/A	November 6032 Bravo Squack ident Radar contact.	4	3 2	10	7 2
	54	G/A	November 6032 Bravo contact Cleveland center one-two-six-point-five-five	9	6 5	15	10,5
	55	A/G	One-two-six-point-five-five	6	4 6	6	4 6
	56	A/G	Cleveland center this Cessna 6032 Bravo one-two-six-point-five-five	6	4,6	16	11 2
	57	G A	November 6032 Bravo Cleveland Center. Change code to zero-one-seven-two Squack ident. Radar contact	11	7 9	19	13 1
	58	G/A	November 6032 Bravo change frequency one-two-seven-point-nine-five	8	5 9	14	9 4
	59	A/G	One-two-seven-point-nine-five				
	60	A/G	Cleveland Center this is Cessna 6032 Bravo one-two-seven-point-five	0	0	16	11 2
	61	G/A	November 6032 Bravo Squack ident Radar contact	6	4 6	10	7 2
	62	G/A	November 6032 Bravo descent to and maintain niner thousand Report leaving fourteen and sixteen thousand Current altimeter three-zero-point-zero-one	18	12 5	24	16 4
	63	A/G	Cessna 6032 Bravo out of flight level* one-eight-zero for niner thousand	6	4 6	16	11, 2
	64	G/A	Roger	1	1 3	1	1 3
	65	A G	Cessna 6032 Bravo passing thru fourteen thousand feet	5	3 9	11	7 9
	66	G/A	Roger	1	1 3	1	1 3
	67	A G	Cessna 6032 Bravo passing three twelve thousand feet	5	3 9	11	7,9
ENROUTE (cont)	68	G/A	Roger	1	1 3	1	1 3
	69	A/G	November 6032 Bravo level at niner thousand	4	3 2	10	7 2
	70	G/A	Roger	1	1 3	1	1,3
	71	G/A	November 6032 Bravo contact Detroit approach control one-two-six-point-five-five	10	7 2	16	11,2
	72	A/G	One-two-six-point-five-five	6	4,6	6	4 6
	73-76	G/A	November 6032 Bravo traffic eleven o'clock west bound 3 miles slow moving	36	24 4	60	40 2
	77-80	A/G	Negative Contact	8	5 9	8	5 9
	81-84	G A	November 6032 Bravo traffic no longer a factor	20	13 8	44	29 6
ARRIVAL	85	A/G	Detroit approach control this is Cessna 6032 Bravo one-two-six-point-five-five level at niner thousand	4	3 2	21	14 5
	86	G/A	November 6032 Bravo change code to zero-one-zero-zero Squack ident Radar Contact	11	7,9	17	11 8
	87	G/A	November 6032 Bravo enter a holding pattern on the one-two-seven degree radial Salem VOR Turns Right Maintain niner-thousand	18	12,5	24	16 4
	88	A/G	Cessna 6032 Bravo one-two-seven degree radial, Salem VOR Turns Right Niner thousand	11	7,9	17	11 8
ARRIVAL (cont)	89	G/A	November 6032 Bravo descend to and* maintain seven thousand, Report passing eight thousand	10	7 2	16	11 3
	90	A G	Cessna 6032 Bravo out of niner for seven	5	3 9	11	7 9
	91	A G	Cessna 6032 Bravo passing thru eight thousand	4	3 2	10	7 2
	92	G/A	Roger	1	1 3	1	1 3
	93	A/G	Cessna 6032 Bravo level at seven thousand	4	3 2	10	7 2
	94	G A	Roger	1	1 3	1	1 3
	95	G A	November 6032 Bravo descend to and maintain five thousand feet. Report leaving six thousand	11	7 9	17	11 8
	96	A/G	Cessna 6032 Bravo out of seven four five	5	3 9	11	7 9
	97	A/G	Cessna 6032 Bravo passing thru six	3	2 6	9	6 5
	98	G/A	Roger	1	1 3	1	1,3
	99	A/G	Cessna 6032 Bravo level at five thousand	4	3 2	10	7 2
	100	G/A	Roger	1	1 3	1	1 3
	101	G A	November 6032 Bravo descend to and maintain three thousand Report leaving four thousand Expect clearance runway two-one at zero-seven-three-five	20	13 8	26	17,8

* Alpha underlined words would be eliminated in an automated system

6.2 QUANTIFICATION OF WORKLOAD MEASUREMENTS BY MISSION

The objective of the workload analysis in the NAVTRACS program was to determine on a relative scale the tradeoff values of different system configurations. No absolute measure of workload was sought. The pilot, copilot and crew were treated as essential system components in the advanced navigation/traffic control system. The essential tasks performed by the crew included:

(1) aircraft control and systems monitor function
(2) navigation management
(3) communications.

It was determined that there is a relatively fixed level of work performed by the pilot and/or copilot in controlling and monitoring the flight path of the aircraft. Quantification of this workload permitted the construction of a baseline of task times and pilot utilization as a percentage of total capability or capacity to do work at any particular instant. On top of this nominal load was placed the percent utilization for the navigation management and communication management functions. Figure 22 illustrates pilot workload for the GA2 user as a function of the operating environment depicted in Figure 23. It is to be emphasized that the workload conclusions provide only relative figures of merit. Substantial simulation is required to validate these numbers. The task-loading depicted in these illustrations pertains to the control and monitor functions only. The results of integrating the complete pilot workload for a VFR flight are shown in Table XXX. Similar summaries are presented in Appendices D, G, and H for all user aircraft considered in this study.

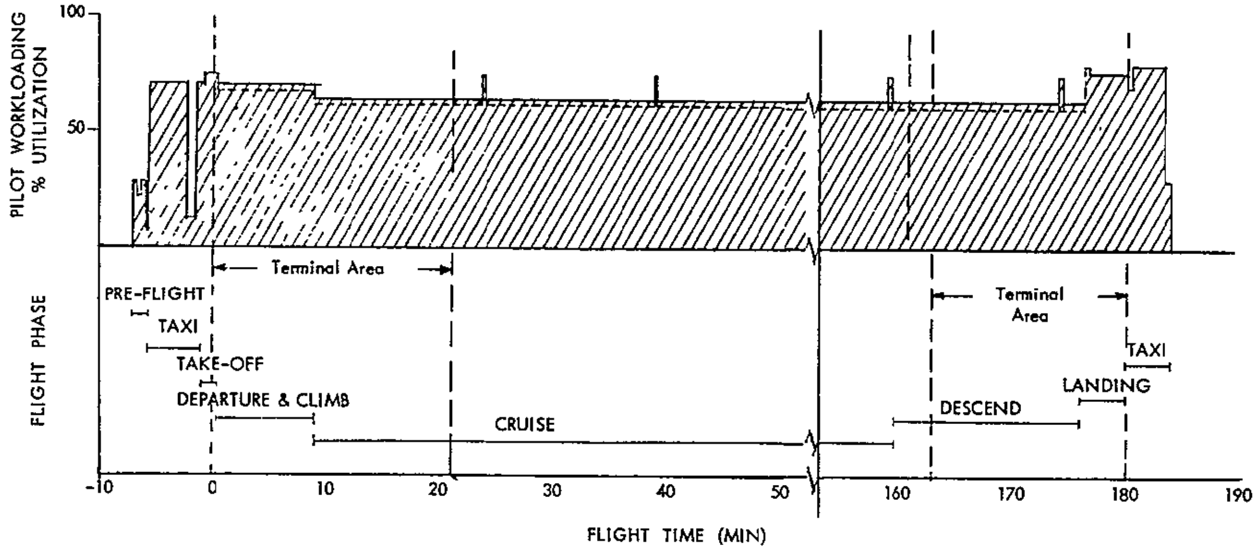
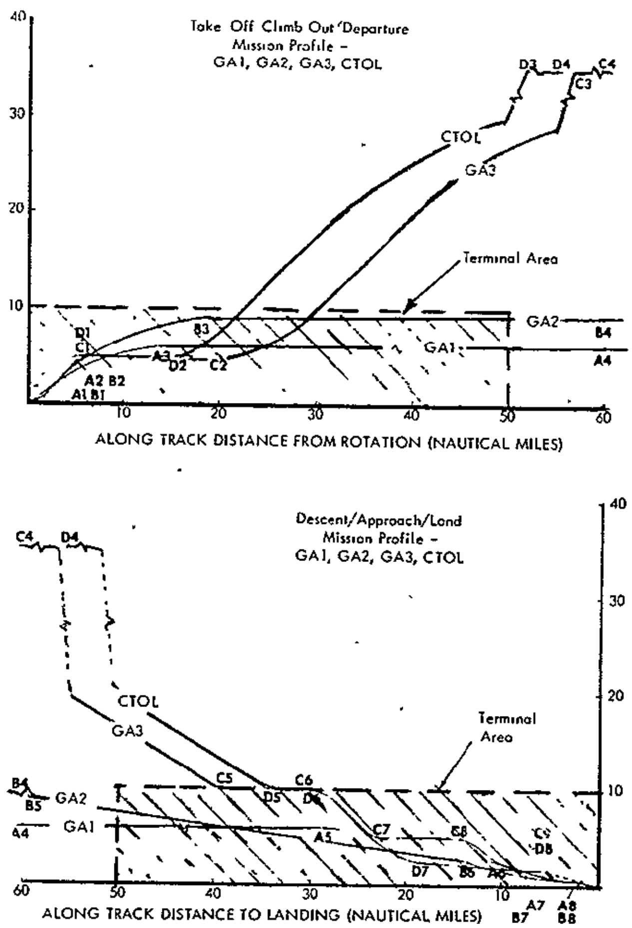


Figure 22. GA2 Pilot Workload Graph



* Figure 23. Nominal Vertical Profiles

* Note:

Figure 8 repeated here for easier reference.

TABLE XXX
GA2 PILOT WORKLOAD

Phase	Pilot Visual Task: Start Time	Pilot Visual Task: Task	Pilot Visual Task: Duration	Pilot Manual Task: Start Time	Pilot Manual Task: Task	Pilot Manual Task: Duration
Taxi	-6.56m			-6 84m	Adjust Seat, Fasten Seat Belt, Lock Doors	17s
	-6.56	Brake Handle	5s	-6.56	Set Brakes	5s
	-6.48	Check Radios and Electrical Switches - OFF	5s			
	-6.39	Ignition Switch	2s	-6 39	Ignition Switch - ON	2s
				-6.36	Crack Throttle	3s
	-6.31	Master Switch	2s	-6.31	Master Switch - ON	2s
	-6.28	Clear Area	7s			
				-6.16	Contact	7s
	-6.04	Monitor RPM, Oil Pressure	20s	-6 04	Adjust Throttle	2s
	-5.71	Check for other Aircraft	5s			
	-5.62	Brake Handle	2s	-5.62	Release Brakes	2s
	-5.59	Check for other Aircraft	3.03m	-5.59	Open Throttle	2s
				-5.56	Control Wheel Rudder, Brakes	3m
	-2.56	Brake Handle	5s	-2 56	Set Brakes	5s
	-2.48	Monitor RPM	2s	-2 48	Open Throttle	2s
	-2 44	Monitor Oil Press	2s			
	-2 41	Monitor Ammeter	2s			
	-2.38	Monitor Oil Temp.	2s			
	-2 34	Monitor Cylinder Head Temp.	2s			
	-2 31	Monitor RPM	4s	-2 31	Check Prop. Pitch Control	2s
				-2 28	Check Left Mag	2s
				-2 24	Check Right Mag	2s
				-2 21	Close Throttle	
	-2 17	Scan Aircraft Control Surfaces	9s	-2 17	Check Free and Correct Movement of Controls	9s
	-2.03m	Scan Flaps and Flap Position Indicator	5s	-2 03m	Check and Set Flaps	5s
	-1 94	Monitor Clock	3s	-1 94	Set Clock	3s
	-1 89	Monitor Altimeter	3s	-1 89	Set Altimeter	3s
	-1 84	Monitor DG	3s	-1 84	Set DG	3s
	-1 79	Scan Rudder and Elevator Trim Position Indicators	5s	-1 79	Set Rudder and Elevator Trim	5s
	-1 71	Scan Fuel Selector Valve Position		-1 71	Check Fuel on Proper Tank	3s
	-1 66	Monitor Frequency Selection	8.6s	-1 66	Set Radio	8.6s
	-1 52	Brake Handle	2s	-1 52	Release Brakes	2s
	-1 48	Check for Other Aircraft	1 05m	-1 48	Open Throttle	2s
				-1 41	Control Wheel, Rudder, Brakes	1 95m
T/O and Departure	-0 45	Monitor Engine Instruments, Airspeed, TK, Altitude, Altitude (5 sec.) every 30 sec.	95s	-.45	Open Throttle	2s
				-.45	Control Wheel Rudder	9m27
				0	Rotate	
				0 05	Retract Gear and Flaps	4s
	0 15	Check Gear and Flaps-Up	3s			
	0 20	Monitor MP	3s	0 20	Adjust Throttles	3s
	0 25	Monitor RPM	3s	0 25	Adjust Propellers	3s
	0 30	Monitor Frequency Selection	8.6s	0 30	Set Radio	8.6s
	0 44m	Monitor Airspeed	10s	0 44m	Adjust Trim	10s
	0 61	Heat and Vent. Control	5s	0 61	Adjust Heating and Vent	5s
	8 86	Monitor Frequency Selection		8 86	Select Frequency	8 6s
		Check for other Aircraft During Remainder of Time			Check for other Aircraft During Remainder of Time	
Cruise	9 0	Monitor Engine Instruments, Airspeed TK, Attitude, Altitude (5 sec.) every 30 sec.	25.12m	9 0	Control Wheel, Rudder	150 7m
	9 0	Monitor MP	3s	9 0	Adjust Throttle	3s
	9 05	Monitor RPM	3s	9 05	Adjust Prop.	3s
	9 10	Monitor EGT	3s	9 10	Adjust Mixture	3s
	9 15	Monitor Mag Heading and DG (10s) every 15 min.	100s	9 15	Update DG every 15 min.	10s
	142 1	Monitor Frequency Selection	8 6s	142 1	Select Frequency	8 6s
Descent	159 7	Monitor Engine Instruments, Airspeed Attitude, Altitude, TK (5 sec) every 30 sec.	190s	159 7	Control Wheel, Rudder	20 75m
	159 73	Check Fuel on Proper Tank	3s	159 7	Adjust Mixture - Rich	2s
	159 78	Monitor MP	3s	159 78	Set Throttle	3s
	159 82	Monitor Airspeed	10s	159 82	Adjust Trim	10s
	175.55	Monitor Frequency Selection	8 6s	175 55	Select Frequency	8 6s
Approach and Landing	175.70m	Monitor Engine Instruments, Airspeed Attitude, Altitude TK (5 sec) every 30 sec.	45s	175.70m	Control Wheel Rudder	4 40m
	175.70	Monitor MP		175.70	Adjust Throttle	3s
				175.75	Adjust Prop - High RPM	2s
	175.78	Monitor Airspeed	2s			
				175.81	Gear Down	7s
	175.91	Check Gear Down	2s			
	175.95	Monitor Airspeed	7s			
				175.98	Flaps Down	3s
	176.03	Monitor Airspeed	10s	176 03	Adjust Trim	10s
	176 20	Monitor Airspeed	3s	176 20	Adjust Throttle	3s
				180 00	Close Throttle	2s
				180 10	Retract Flaps	2s
		Check for Other Aircraft During Remainder of Time				
Taxi				180 45	Control Wheel Rudder, Brakes	3m
	180 45	Monitor Frequency Selection	8.6s	180 45	Select Frequency	8.6s
	183 45	Brake Handle	5s	183 45	Set Brakes	5s
	183.53	Radio and Electrical Switches	5s	183 53	Radio and Electrical Switches - OFF	5s
	183.62	MIXTURE Control		183 62	Adjust Mixture -LEAN	2s
	183.73	Mag Switch	2s	183.73	Mags - OFF	2s
	183.77	Master Switch		183 77	Master - OFF	2s

6.3 SYSTEM-LEVELS OF AUTOMATION, NAVIGATION MANAGEMENT

A preliminary ground rule laid down at the outset of this study was the utilization of the area navigation concept as part of the postulated ATC system. In this regard, it is evident that there are several different approaches one might take to implementation of systems on the flight deck. These approaches might be treated as different levels of automation and complexity. As a part of the emphasis on pilot-related factors, the effect of automation on the navigation and communication management functions and pilot workload were studied in depth.

All of the workload studies were related to a minimum automation baseline system consisting of a simple course-line computer (CLC) operating in conjunction with VOR/DME. In the case of the navigation function, the level of pilot workload is directly affected by the type of navigation aids used, therefore various levels of automation were investigated for both the rho-theta system (VOR/DME), typical ground based time difference systems (GBTD) and NAVSAT.

A summary of the levels of automation which were investigated is shown below. Table XXXI describes fourteen configurations of equipment and/or levels of automation postulated for general aviation, GAI and GA2, aircraft. Workload assessments were completed for each configuration. Tables XXXII and XXXIII describe the ten configurations of equipment evaluated for GA3 and the air carrier aircraft. All of the systems are briefly described in Section 6, Volume II, and discussed in detail in Appendices D, G, and H of Volume III.

In general these systems provided the following navigation-related capabilities:

1) Use of full area navigation capability, including implemention of the Flight Plan Reference System into a general purpose airborne computer. The incremental effect of a moving map display was also evaluated but is not shown on this summary. It was shown to reduce workload by 10%.
2) The introduction of coded terminal waypoints into the area navigation computer, in order to relieve the high demands upon pilot attention in the terminal phase of the flight.
3) Automation of the flight plan insertion process, which can reduce workload not only on the ground but in the air. It should be noted that the system must retain the capability to introduce or receive an amended clearance.
4) Implementation of the Limit Logic concept; that is the automatic process used onboard the aircraft to continually compare actual flight progress with the approved (and stored) flight plan. Full utilization of Limit Logic requires that the Flight Plan waypoints and connecting flight paths be stored in the system and automatically made available to the Limit Logic subroutine as the aircraft proceeds along track.

Table XXXIV illustrates the effects of the foregoing levels of automation on pilot execution time for a typical navigation kanagement task by flight phase. Figure 24 summarizes

TABLE XXXI
GAI, GA2 AIRBORNE SYSTEM CONFIGURATIONS

USER	General Aviation System - Levels Of Automation	NAVIGATION: UHF (VOR) NAV/COMM Receiver	NAVIGATION: UHF DME NAV Rec.	NAVIGATION: UHF NAV SAT Rec. - Manual Acq.	NAVIGATION: UHF NAV SAT Rec. - Auto Acq.	NAVIGATION: LF Ground Based TD Rec. - Manual Acq.	NAVIGATION: LF Ground Based TD Rec. - Auto Acq.	NAVIGATION: NAV SAT Ephemeris Data Tables	MAPS: Local Aeronautical Chart	MAPS: Local Aeronautical Chart - GB TD Contours	COMPUTERS: Hand Held DR Computation Aid	COMPUTERS: DR AT/CT Computer	COMPUTERS: GB TD Computer	COMPUTERS: Course Line Computer	COMMUNICATION: VHF Voice Link	COMMUNICATION: VHF Data Link - Min.	COMMUNICATION: VHF Data Link - Max.	GROUND SYSTEM: NAV SAT PF and Guidance, DR	GROUND SYSTEM: GB TD PF and Guidance, DR	GROUND SYSTEM: Storeable Flight Plan
GA1, GA2	g1			x				x	x		x				x			x		
GA1, GA2	g2				x			x	x		x				x			x		
GA1, GA2	g3					x				x	x				x				x	
GA1, GA2	g4						x			x	x				x				x	
GA1, GA2	g5				x			x	x		x				x			x		x
GA1, GA2	g6						x			x	x				x				x	x
GA2	g7				x			x	x		x				o	x		x		x
GA2	g8						x			x	x				o	x			x	x
GA2	g9				x				x			x			x	x		x		x
GA2	g10				x				x			x			o		x	x		x
GA2	g11						x			x			x		x	o				x
GA2	g12						x			x			x		o		x			x
GA2	g13	x	x						x						x					x
GA2	g14	x	x						x					x	o		x			x

x: Also used with navigation units g1, g2, g5 and g7

o: Voice as backup

TABLE XXXII
GA3, AIRCARRIER AIRBORNE SYSTEM CONFIGURATIONS

AIR CARRIER AND GA3 SYSTEMS - LEVEL OF AUTOMATION	NAVIGATION						CONTROL DISPLAY		COMPUTERS			COMMUNI-CATIONS (o - voice as backup)		GROUND SYSTEM
	VOR NAV Comm Rec. DME Rec.	UHF NAV SAT Rec.	LF GBTD Rec.	Air Data	Doppler	INS	Control/Display Unit	MMD	Course Line Computer	Area NAV Computer	Area NAV Vertical Channel	VHF Voice Link	VHF Data Link	Flight Plan Reference
v1			x	x			x			x	x	o	x	x
v2			x	x			x	x		x		o	x	x
v3			x		x			x		x		o	x	x
v4			x	x		x	x			x		o	x	x
v5		x		x			x			x	x	o	x	x
v6		x			x			x		x	x	o	x	x
v7		x				x	x			x		o	x	x
v8	x				x				x			o	x	x
v9	x				x					x		o	x	x
v10			x		x			x		x		o	x	x

TABLE XXXIII
CANDIDATE SYSTEM USERS

SYSTEM	Domestic System Route Structure Use	VTOL	VTOL/ Helicopter	STOL	GA3/ CTOL	SST
v1	Short Haul	x		x	x	
v2	Short Haul	x		x		
v3	Short Haul - Terminal Area Altitudes	x	x	x		
v4	Long Haul				x	x
v5	Short Haul	x		x		
v6	Short Haul - Terminal Area Altitudes	x	x	x		
v7	Long Haul				x	x
v8	Short/Long Haul	x	x	x	x	x
v9	Short Haul	x	x	x	x	
v10	Short Haul*	x	x	x		

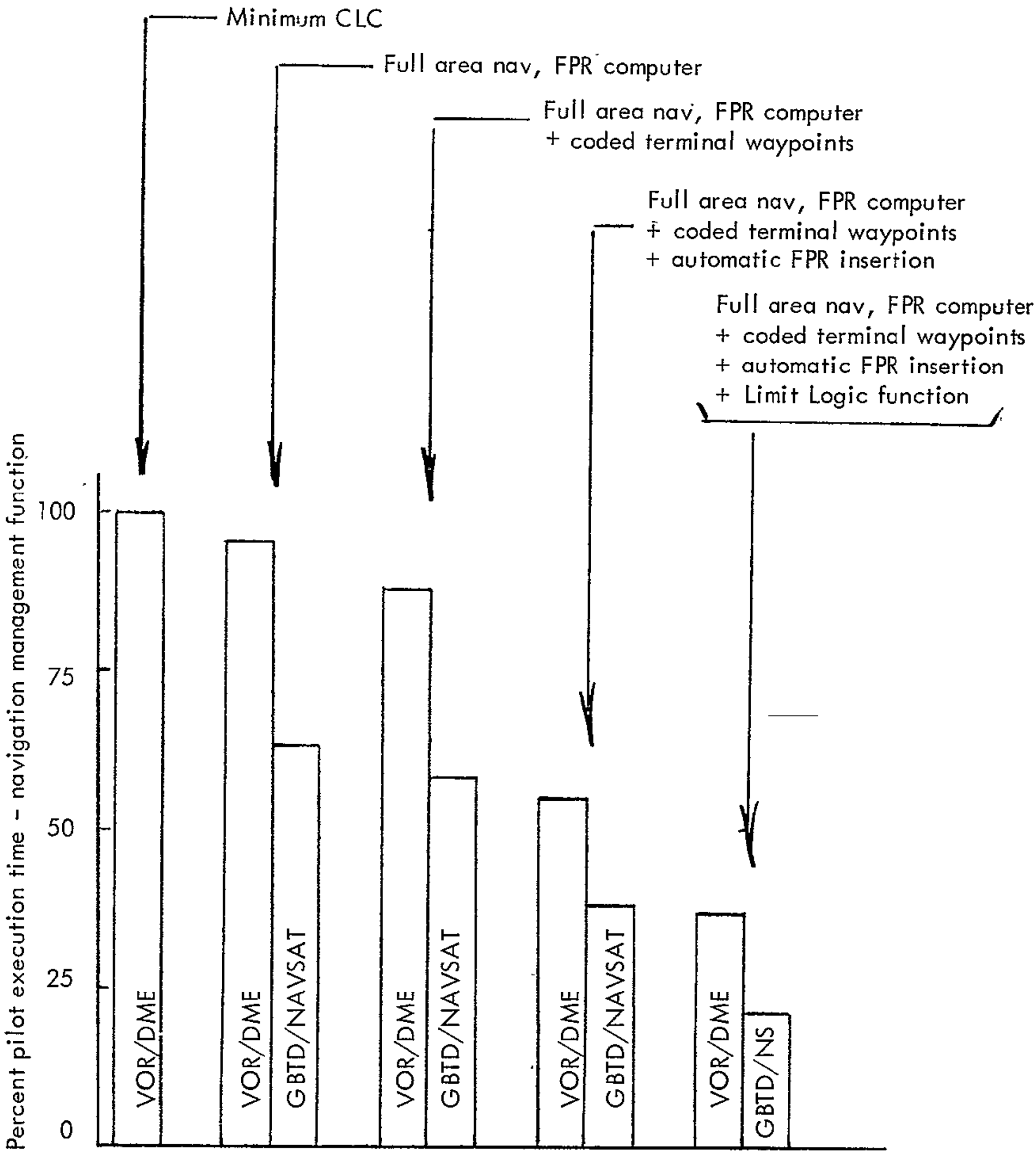
*Air Taxi

the possible relative reduction in percentage of pilot execution time, or workload, from use of the systems indicated for the entire flight.

TABLE XXXIV

PILOT EXECUTION TIME, NAVIGATION MANAGEMENT TASK
All units are seconds.

	Automation Level (cumulative	Flight Phase: Preflight and taxi	Climb & depart	Enroute cruise	Terminal & arrival	Landing and taxi	Total
	Minimum area nav CLC with VOR/DME	70	210	1320	310	10	1920
VOR/ DME	Full area nav, flight plan reference computer	720	100	680	220	10	1830
	+ Coded terminal waypoints	720	100	440	220	10	1690
	+ Automatic Flight Plan Reference insertion	80	100	440	220	10	1050
	+ Limit Logic function	80	100	110	220	10	720
GBTD & NAV SAT	Full area nav flight plan reference computer	430	70	520	180	10	1210
	+ Coded terminal waypoints	430	70	430	180	10	1120
	+ Automatic Flight Plan Reference insertion	40	70	430	180	10	730
	+ Limit Logic function	40	70	100	180	10	400



* FPR: Flight Plan Reference

Figure 24 Cockpit Workload Reduction, Navigation (Through Navigation Management Automation, Typical IFR Flight)

6.4 SYSTEM LEVELS OF AUTOMATION, COMMUNICATION MANAGEMENT

Automation of the present voice communications link through use of a data link system can result in a substantial reduction in the total communications task execution time. Complete discussion will be found in Section 6 (System Automation) of Volume II-Technical, and Appendix D (Pilot Workload Analysis) of Volume III - Appendices, of this report. The four levels of automation contained in this analysis are:

1) Automation of the standard position report-utilizing the airborne derived surveillance data generated by the area navigation computer, transmitted upon demand or automatically at specified fix positions.

2) Automation of the ground-to-air (G-A) command and control instructions. This function was assumed to be implemented by a direct input to the airborne computer via data link from the ground complex and subsequently displayed on a CRT or a teleprinter.

3) Automation of the air-to-ground (A-G) acknowledgement of the previous G-A message, including the decision of the pilot to accept or reject the specific command message.

4) Automation of the receipt of advisory information (airfield, weather, traffic, etc.) via data link, also to be displayed on either the CRT or teleprinter readout device.

Using the results of the pilot workload analyses, and using the current voice communication techniques as a baseline, the following table illustrates the cumulative effect during various phases of flight of implementing the varying levels of automation on the total pilot execution time devoted to communications. Figure 25 portrays the overall reductions in percentage of pilot execution time, or workload, for the entire flight. A typical IFR GA3/CTOL flight was used as this illustrative example. Similar analyses are contained in the basic report for GA1, GA2, and VTOL/STOL aircraft. (See Volumes II and III.)

TABLE XXXV
PILOT EXECUTION TIME (IN SECONDS PER FLIGHT PHASE) COMMUNICATION TASK

Automation Level (cumulative)	Flight Phase					
	Pre-flight and taxi	Climb & depart	Enroute cruise	Terminal arrival	& Landing and taxi	Total
Voice/manual	165	155	365	235	45	965
+auto. std. position report	165	120	300	160	30	775
+auto. A-G acknowledge	140	100	220	150	15	625
+auto. G-A command	130	50	35	120	10	345
+auto advisory	30	40	30	30	10	140

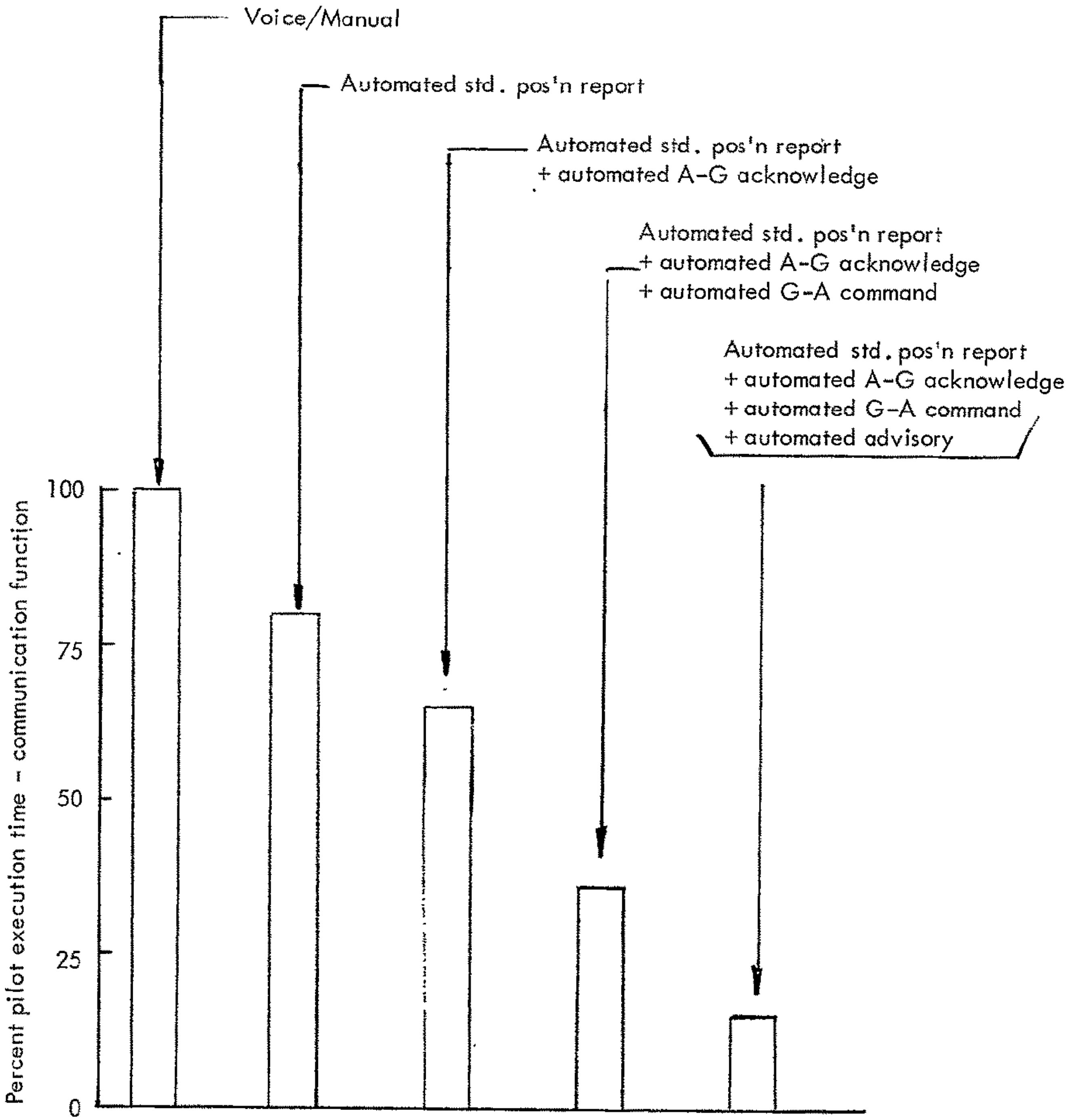


Figure 25. Cockpit Workload Reduction, Communication (Through Communication Automation, Typical IFR CTOL Flight)

7. SYSTEM RANKING

As a necessary element of this study, a relative ranking of the candidate navigation systems was performed. Although any ranking or weighting criteria is, in some degree, arbitrary, nevertheless sufficient quantitative data was generated during the study to allow a reasonable evaluation to be made. System Capacity Benefit and System Cost Benefit were chosen as the two criteria to be used to provide a measure of the relative effectiveness of six candidate navigation configurations--navigation satellite (NAV SAT), ground based time difference (LF-CW, VLF-CW, LF-pulsed) and precision rho-theta. The criteria rank the area navigation systems in relative order of acceptability for integration with the Flight Plan Reference System--the recommended ATC system.

The System Capacity ranking was generated by relating system accuracy and pilot workload in the following manner:

$$\text{Relative Capacity Index} - C_R = \frac{P_s \text{ (baseline system)}}{P_s \text{ (candidate syttem)}}$$

where $P_s = A \cdot (B+C)$

and A = System 3 σ accuracy

B = GA pilot communication and navigation management execution time

C = Air carrier pilot communication and navigation management execution time

For this evaluation the P_s for the rho-theta system configuration was taken as the baseline value.

Decreasing C implies that an improvement has been made in the cockpit environment through automation; for example the pilot of the commercial aircraft is better able to comply with short-notice changes in some traffic control parameter, yet he is still able to perform other required management tasks. In a similar way, decreasing B implies an improvement in the general aviation pilot workload, the pilot becomes better able to cope with the advanced traffic control system. Decreasing (improving) A implies the availability of more accurate surveillance data and the potential for closer spacing of tracks. Table XXXV presents the quantities A, B and C for each of the six systems, subsequently ranked in Table XXXVI.

If the System Capacity index is further refined with a measure of ground system station and maintenance costs, the following performance index is obtained:

$$C_s = \frac{C_R}{C_{\$R}}$$

where $C_{\$R} = \dfrac{\text{Cost (candidate system)}}{\text{Cost (baseline system)}}$

As in the Capacity index, the baseline system used in this cost index is the rho-theta system. The cost of each system was based on the overall cost of implementing the total number of ground stations of each type required to give complete area coverage of the domestic U.S. No attempt was made to separate out the cost incurred to date for existing installations. Table XXXVII presents the baseline cost data used in preparation of Table XXXVIII which contains the relative ranking of aids. Section 7 (System Benefit) of Volume II-Technical of this report contains more detailed information on this subject.

Both ranking systems show that, for those systems which meet the 1975-1985 area navigation/traffic control operational requirement, the NAV SAT system offers the greatest benefit, followed by Loran C, Decca and PVOR/PDME, in that order. The relative rankings of these systems does not change with addition of the differential time difference capability for use in meeting the landing aid criteria.

Volume II (Technical)

*Section 6.3
**Section 5 (Figure 31)
***Section 6.3.1 (Figure 62)
****Section 6.3.2 (Figure 81)

TABLE XXXVI
AREA NAVIGATION SYSTEM PENALTY CRITERIA

CANDIDATE SYSTEMS*	A** System Accuracy nmi	B*** General Aviation Pilot Comm. and Nav. Management Workload Total Mission Execution Time, seconds	C**** Air Carrier Pilot Comm. and Nav. Management Workload Total Mission Execution Time, seconds
Rho-theta (g13, v8)	1.3	4520	1510
Precision rho-theta (g14, v9)	0.5	3390	895
GBTD-VLF/CW (g12, v2)	6.6	3110	705
GBTD-LF/CW (g12, v2)	0.5	3110	705
GBTD-LF/Pulsed (g12, v2)	0.5	3110	705
NAV SAT (g9, v5)	0.1	3340	705

TABLE XXXVII
SYSTEM CAPACITY BENEFIT RANKING

System Type	Example	C_R
NAV SAT	NAV SAT	19.3
LF GBTD-Pulsed	Loran C	4.1
LF GBTD-CW	Decca	4.1
Rho-theta	PVOR/PDME	3.7
*Rho-theta	VOR/DME	1.0
*VLF GBTD-CW	Omega	0.35

TABLE XXXVIII
ESTIMATES OF GROUND STATION AND MAINTENANCE COSTS

System Type	Single Station Total Cost $\$ \times 10^6$	Ground Station Yearly Maintenance Cost $\$ \times 10^6$	Ground Station Cost $\$ \times 10^6$	Estimated* Number of Installations	Total Cost $\$ \times 10^6$	$C_{\$R}$
VOR/DME	0.23	0.03	0.2	1500	350	1
VLF GBTD-CW	9.3	0.3**	9.0	4	37.2	0.106
PVOR/PDME	0.23	0.03	0.2	1500	350	1
LF GBTD-CW	1.55	0.05	1.5	60	93	0.265
LF GBTD-Pulsed	4.4	0.2	4.2	7	31	0.08
NAV SAT	106	---	---	1	106	0.3

**estimate

*for domestic airspace coverage; based on 75×10^5 nmi^2, and effective, high accuracy circular coverage as follows:

LF GBTD-LF : 1.3×10^5 nmi^2

LF GBTD-Pulsed : 11.3×10^5 nmi^2

TABLE XXXIX
COST-WEIGHTED SYSTEM RANKING

System Type	Example	C_s
NAV SAT	NAV SAT	64
LF GBTD-Pulsed	Loran C	51
LF GBTD-CW	Decca	15
Rho-theta	PVOR/PDME	3.7
*VLF GBTD-CW	Omega	3.3
*Rho-theta	VOR/DME	1

*Do not meet the 1975-1985 area navigation/traffic control operational requirements.

8. SUMMARY AND CONCLUSIONS

8.1 GENERAL

The purpose of this study was to supply the NASA with insight to desirable operational characteristics of an advanced air traffic control system designed to accommodate the expected general aviation and air carrier traffic forecast to be operational in the 1975 - 1985 time period.

In this effort the point of view of the user of the system was to be the principal criterion of acceptability. Forecast traffic densities for both the enroute and terminal airspace were used to define required system capacity. A mix of user aircraft which included three categories of general aviation aircraft and four categories of commercial carrier was assumed.

Assumptions were made about the availability and performance of six candididate navigation systems; Decca, Loran C. NAV SAT, PVOR/PDME and a hybrid radio-inertial system. For completeness, Omega was also considered.

Because none of the systems mentioned above completely satisfied the requirements set for the all-weather landing phase of flight, a highly accurate, modified version of each of the Time-Difference Aids (Decca, Loran and NAV SAT) was postulated and evaluated.

8.2 STUDY METHODOLOGY

A straw-man ATC system was configured around the postulated air transportation system requirements. A basic assumption carried throughout the entire study was that all aircraft forecast to be active in the 1975-1985 time frame had to be accommodated with minimum delay, as near to the direct and optimum flight path as could be achieved, and with absolutely no compromise to safety. In addition, the system was to rely as much as possible on the existing ATC structure; that is, it should be evolutionary in nature.

Identification of the principal system performance requirements was determined from an analysis of user aircraft, traffic forecast, and missions as they affected navigation, communication, and pilot information requirements. Review of air crew comments and recommendations regarding deficiencies of the existing system were combined with system capacity requirements to establish the overall desired operational characteristics and performance requirements.

In order to determine the effect on pilot workload of various system configurations, a comprehensive mission and workload evaluation model, called Event Sequence Diagrams, was developed for this study. The effect on pilot workload of various levels of automation and candidate navigation system technologies was performed.

Ground system implementation cost figures were also developed for the candidate systems, as well as was an evaluation of the relative ability of the candidate systems to meet the performance criteria. The sets of information were then subjected to careful analysis, thereby permitting the nomination of a most promising candidate system along with a relative ranking of all systems considered.

8.3 CONCLUSIONS

There were seven major conclusions arrived at as a result of this study:

(1) In order to accommodate the number and varieties of aircraft anticipated to be operational in the 1975-1985 time period, all aircraft operating in controlled airspace will be required to file a flight plan whether operating VFR or IFR. Perhaps the major constraint on increasing system capacity is the navigation and communication performance capabilities of the GA aircraft.

(2) To reduce the requirements on the communication system, pilot, and ATC controller, a procedure which minimizes communications and the necessity for radar flight following, i.e. the Flight Plan Reference with Limit Logic concept (control-by-exception) recommended in this study should be adopted.

(3) In order to accommodate all the expected users of the system, a means should be found to provide unambiguous navigation, position, and surveillance information allowing parallel and slant track operation, i.e. implement a three dimensional area navigation system of high precision.

(4) Automation of the communication link is required in order to accommodate all the traffic seeking to use the system. This automation will relieve pilot and controller workload, facilitate the use of airborne-generated navigation surveillance data, keep the surveillance data free of human error, and enable the implementation of Limit Logic (control-by-exception) capability.

(5) Significant improvements in the cockpit environment should be made in both the air carrier and general aviation aircraft through reduction of workload. The greatest need and also the greatest potential pay-off in terms of increased system capacity is related to the GA cockpit.

(6) Acceptable navigation system candidates are NAVSAT, Decca, Loran C and PVOR/PDME.

(7) The most promising candidate system for both general aviation and air carrier use is the NAVSAT system.

9. RECOMMENDATIONS

It is clear from review of the major elements of this study that success in design of a safe, economic and efficient air transport system which will accommodate all air carrier and general aviation vehicles seeking to use the system will require considerable improvements in accuracy of navigation and facility of communication, reduction in cockpit workload, increased awareness and advance notice of hazards to flight, and significant increase in flexibility in the ATC system.

These improvements must be made available to all levels of GA users, thereby necessitating that the selected solutions be compatible with the financial capability of the GA1 pilot. This user is characterized as having the least experience but the highest level of cockpit workload. As a consequence considerable research and development is recommended in the area set out below. . . . . solutions should be sought which are aimed in particular at GA1 and GA2 users.

Because of the potential that VTOL and STOL aircraft will have to relieve congestion within the major terminal areas and large hubs through utilization of small, relatively low cost satellite airports and landing pads, large gains in system capacity can be realized from enhancing their ability to utilize regions of the airspace not now required or contemplated for use by CTOL jets, SST and GA aircraft. In summary then, it is recommended that NASA concentrate its search for improved technologies in those areas which will result in the greatest improvement in operational capability of GA1, GA2 , VTOL and STOL aircraft.

The following general areas of research would seem to offer the earliest and most significant payoffs.

(1) Increase system capacity by supporting development of a precise area navigation capability to include approach and land phase of flight capable and acceptable of use by GA1 and GA2 aircraft.

(2) Improve the communication environment through development of an automated command, control and surveillance link, and a non-voice advisory information system.

(3) Implement a cockpit workload reduction program which includes development of simplified information displays, automated area navigation and surveillance aids a low cost general purpose computer capable of accepting the recommended Flight Plan Reference and Limit Logic and an automated communications link. A pre-requisite is the development of algorithums permitting simulation and thus validation of the estimated system capacity benefits.

(4) Develop an air transportation system evaluation tool which can be used to relate aircraft, missions, pilot and systems to an air traffic control environment

for the purpose of validating the workload conclusions of this and other studies. It should also provide the means to perform sensitivity analyses and tradeoff studies. related to system-levels of automation or variations in basic parameters affecting system capacity.

(5) Perform a series of operations analysis studies. Use these to permit determination of requirements and benefits related to ATC path stretching, speed scheduling, standardization of area navigation procedures so that computer and I/O hardware complexity can be reduced. Extend the sensitivity analysis on capacity and cost benefits of candidate systems initiated in this study.

APPENDIX A

STATEMENT OF WORK

STATEMENT OF WORK

1. The objective of this procurement is to identify, from a pilot's viewpoint, desireable performance characteristics of an advanced navigation/traffic control system for aircraft operating in a mixed V/STOL, jet, SST, general aviation environment, emphasizing V/STOL aircraft, and to configure and evaluate promising candidate system concepts.

Statement of Work

Polhemus Associates, Inc. (PAI) will supply the necessary personnel, facilities, services, and materials to accomplish the following:

A. Identify the features of an air traffic control system which are required in a mixed V/STOL, jet, SST, general aviation environment. The contractor is encouraged to define the critical attributes of the system but should consider data requirements, accuracies, sequencing, and other operational constraints. Identify the features of an area navigation, approach and landing system required for aircraft operating in the mixed ATC environment. Study the applicability of high-quality navaids such as Decca, Loran C, NAV/SATS, in conjunction with on-board radio inertial instruments as sources of accurate navigational data for area, approach and landing for V/STOL and other aircraft and/or independent sources of position/velocity data for ATC. Configure promising candidate navigation/traffic control systems.

B. Perform pilot workload analyses for V/STOL, SST, jet, and general aviation classes of aircraft in the conceptual navigation/traffic control environments configured in A. Perform economic tradeoffs for both ground and aircraft installations. Select a most promising configuration in terms of cost and pilot workload and identify areas where a greater degree of automation could improve the effectiveness of the navigation/traffic control system significantly.

C. Outline field experiments required to demonstrate critical attributes of the most promising configuration.